Space Syntax and Spatial Cognition

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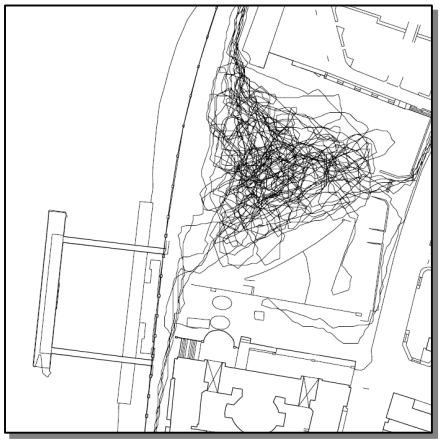
Christoph Hölscher, Ruth Conroy Dalton, Alasdair Turner (Eds.)



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SPATIAL COGNITION

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Understanding Space: the nascent synthesis of cognition and the syntax of spatial morphologies

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The Workshop

In September 2006, a one-day workshop took place that formed an opening session of the Spatial Cognition '06 Conference, and was held in Bremen, Germany. The theme of this workshop was space syntax and spatial cognition and it represented the culmination of an idea first mooted at the Spatial Cognition '04 conference (Frauenchiemsee, Germany) and furthered developed by discussions at the Fifth International Space Syntax Symposium in Delft, 2005. The significance of this workshop was, at one level, personal: for some time researchers into space syntax at University College London and into spatial cognition at the Transregional Collaborative Research Center SFB/TR 8 Spatial Cognition (Universities of Bremen and Freiburg) had been seeking ways to initiate an interdisciplinary collaboration. Such an opportunity, as this workshop represented, to bring together the two wider research communities formed a vital strand of this ambition: our expectations, however, were perhaps more modest – we were simply planning a day of interesting discussions and debates in order to establish an agenda for any future collaboration. In reality, the response of the conference delegates far exceeded our expectations and the quality of participation was extremely high. The workshop was attended by thirty-three academics, from as far a field as the USA, Australia and Japan and representing a wide range of academic disciplines (architecture, geography, psychology, computer science and the social science). During the course of a lively and stimulating day, ten accepted papers were presented (out of eighteen originally submitted) as well as a number of posters. The high quality of the accepted papers owed much to the diligence of our stellar programme and reviewing committee[1], in whom we were particularly fortunate.

[1] Dennis Doxtater (U. Arizona); Gerald Franz (MPI Biocybernetics, Tübingen); Saif Haq (TexasTech); Ben Kuipers (Austin); Alan Penn (UCL London); John Peponis (Georgia Institute of Technology); Juval Portugali (Tel Aviv University); Martin Raubal (Universität Münster, now at UC Santa Barbara); Roy Ruddle (U. Leeds); Barbara Tversky (Stanford); Jan Wiener (College de France, Paris); Jean Wineman (U. of Michigan); Craig Zimring (Georgia Institute of Technology); Gerald Weisman, University of Wisconsin-Milwaukee.

The original call for papers proposed a series of theoretical and methodological topics, which the workshop organizers felt formed a general framework of the issues that needed to be addressed as part of any future collaborative research programme.

The theoretical topics were:

- How can the cognitive processes of individual users be addressed by space syntax?
- How should space syntax methods be adapted to make the transition from the social/group level to individual cognition?
- Does space syntax help us to better understand the cognitive import of physical properties of the environment like complexity, visibility, legibility, intelligibility?
- What is the correspondence between space syntax measures and cognitive processes?
- Can we map concepts such as 'intelligibility' to cognitive processes or human memory?
- How can network effects be separated from psychological effects?
- Can spatial cognition reveal the 'non-discursive' features of the design process?

Methodological topics according to the call for papers:

- Collecting behavioural data for space syntax analysis.
- Space syntax of complex indoor settings (multi-level, visibility vs. walkability, etc.)
- Global, local, route-specific measures.
- Axial analysis, visibility graph analysis.
- Finding the right computational tools for space syntax analysis.
- How to design experiments to validate space syntax theory.
- Systematic variation of environmental properties vs. correlational studies.
- Simulated environments and agents as methodological tools.

The relative importance and relevance of some of these issues can be evidenced in the papers themselves, which essentially speak for themselves (and most eloquently). Suffice to say, that as a research agenda, the organizers of the day felt that they provided a set of real problems that urgently need to be addressed: a set that could never be addressed in just a single workshop, but should perhaps be held up as an agenda for future research endeavour.

What is space syntax?

Space syntax is a term that is used to describe a family of theories and techniques concerning the relationship between space and society. It emerged from a dynamic and active research group based at University College London, in the early 1970s, and led by Professor Bill Hillier. The original driving force behind space syntax research was prompted by a goal to understand the relationship between space and society (rather than space and an individual subject) (Hillier and Hanson, 1984). Initially it

was thought that by holding a 'spatial configuration[2]' to be an artifact of the society that constructed it, then by studying such a system of spaces, it should be possible to more fully understand the society itself (as would be true of studying any other kind of artifact). However, the relationship between space and society is a two-way relationship: not only does a society create the spatial systems that it uses, but a group of people (be it the inhabitants of a settlement, an urban neighbourhood or the users of a complex building) is directly affected and influenced by the spaces they inhabit. In particular, one extremely powerful way in which a pattern of spaces, or a configuration, affects its users is through pedestrian movement. Any set of spaces, of sufficient complexity to be described as a configuration, forms a spatial hierarchy in which some spaces become more strategic and others less so. These strategic or, on average, more accessible spaces will tend to attract a higher rate of pedestrian movement than other, more segregated, spaces. This is clearly explained in Bafna's excellent introduction to space syntax (Bafna, 2003). One of the key methods of analysis used in space syntax research is a graph-based technique that is able to identify and represent this varying pattern of more-to-less strategic spaces. Although such techniques were not originally developed as tools for predicting pedestrian movement, it has been found that there does exist a powerful relationship between movement and spatial structure and so this graph-based analysis may be used to predict relative rates of pedestrian flow. It is this predictive ability of space syntax analyses that has caused it to be adopted as a design tool by many architects and urban planners.

The terms space syntax betrays its early analogies to linguistic theories. It was felt that, just as there is a limited combination of words, which can be assembled into a meaningful sentence, there are a limited number of meaningful spatial configurations. Although it is possible to generate (using generative algorithms) a near-infinite number of, for example, building plans, only a small number of these bear any relationship to real-world designs (Hillier, 1996). The linguistic analogy is that although it is possible to randomly generate grammatically correct sentences, only a small number of these would make any sense. The conclusion is that configurations of spaces have not only a grammar, but also a 'syntax': the pattern of relationships between spaces. It is this pattern of spatial relations that permit configurations to be meaningful and it is hypothesized that people have an innate ability to 'read' or comprehend these meanings. It is this aspect of attempting to understand how the meaning of spatial environments is communicated that connects space syntax to other academic fields interested in environmental cognition. How is it that a spatial configuration becomes meaningful? How are meanings transmitted? How are the understood? What range of meanings is encapsulated?

By starting to ask such questions, the centre of space syntax research starts to shift its emphasis from society as a whole (i.e. the origins of space syntax) to a line of enquiry that is firmly focused on the individual. And this, in turn, can be seen as the start of the journey which leads to a potential convergence with disciplines such as

[2] A configuration, in space syntax terminology, is a set of spatial relations in which each relationship affects, and is affected by, all others; the modification of any single spatial relation, will have an affect on the whole configuration. Usually, a configuration is of such complexity that words do not exist to describe it in the way that words such as 'adjacent' and 'between' can be used to describe a more simple spatial relationship.

psychology that have their origins in the relationship between an individual and their context. Along this journey, there have been certain significant landmark events.

Finding the Building in Wayfinding

In 1990 a paper was published in the journal Environment and Behaviour, called *Finding the Building in Wayfinding* by Peponis, Zimring and Choi from the Georgia Institute of Technology. Zimring was (and still is) an environmental psychologist who has spent the majority of his career working with architects and in architectural academia. His early research emerged from the North American tradition of research into environmental psychology and environmental behavioural research (exemplified by organizations such as EDRA, the Environmental Design Research Association, and by techniques such as post-occupancy evaluation, POE), which developed at the end of the 1960s. Peponis, in contrast, is an architect and academic, and in 1990 had only just arrived at Georgia Tech, from the London space syntax group, where he had worked closely with Hiller, his doctoral supervisor.

Zimring and Peponis' first collaboration produced one of the most, to this day, highly cited space syntax papers as well as being one of the most highly cited papers on wayfinding. The key behind the success of this paper was their realisation that the majority of wayfinding research, at that point in time, had failed to take account of the spatial variables involved in how we navigate around complex environments: hence the title of the paper. This paper presents the results of a pioneering wayfinding experiment, in which correlations were found between measures of a building's spatial configuration and indicators of wayfinding performance: the authors not only conducted a 'classic' wayfinding experiment but attempted to set that against detailed spatial analyses of the experiment setting. This paper is held to be significant for this reason, but, in the context of this introduction, it further represents the first time that a mainstream paper attempted to address this interface between the individual and their cognition of a complex spatial system against a background of space syntax research. This paper can therefore be seen to have paved the way, not only for future research into wayfinding and navigation but, more importantly, for this shift of focus of space syntax itself.

The next milestone in the convergence of space syntax and spatial cognition was the 2001, or Third, International Space Syntax Symposium, which also happened (perhaps not coincidentally) to have taken place at the Georgia Institute of Technology. Among the line-up of invited keynote speakers, were Barbara Tversky, Benjamin Kuipers and John O'Keefe, three people who, from their difference perspectives (psychology, AI/robot navigation and neuroscience) have made some of the greatest contributions to the field of spatial cognition. At this symposium there was a clear and identifiable group of papers, which were engaging with spatial cognition. A selection of the best of these were revised and re-published as a special issue of Environment and Behaviour, edited by Conroy Dalton and Zimring (Issue 1, 2003).

The Fourth International Space Syntax Symposium, in London in 2003, elicited some highly relevant papers on space syntax and spatial cognition, not least of which

was Hillier's attempt to determine whether there is a syntax of spatial cognition (2003). He argued that the actively cognizant individual plays a vital role the shaping and functioning of the city. In particular, Hillier was concerned with subjects' cognition of the urban grid, and how this becomes internalized in a manner that is both perceptual and conceptual, "serving at once as an abstracted representation of the space of the city and as a means of solving problems, such as navigational problems." Hillier went on to debate how it is that we acquire such a concept of the urban grid. In addition to Hillier's paper, a plenary talk by Conroy Dalton, presented originally as a response-talk to a keynote by Tversky, introduced the idea of the typical spatial representations used in space syntax being, what Conroy Dalton termed, 'embodied diagrams', namely diagrams that are imbued with a manifold set of meanings pertaining to the experience of being embodied within an everyday spatial context. This talk was put together with the intention of laying the foundations of the common ground shared between space syntax and spatial cognition. The text of the oral-only presentation was subsequently published as a paper in World Architecture Magazine in 2005 (Conroy Dalton 2005).

2005 was also the year of Hillier and Iida's most recent paper on spatial cognition, a significant paper on the psychological effects of urban movement in which the authors ask whether *"the correlations that are found with syntactic variables at the level of aggregate flows are due to cognitive factors operating at the level of individual movers, or… are simply mathematically probable network effects"?.* The data underpinning this paper is extremely thorough and hence persuasive of the paper's suggestion that geometric (perception of angles turned while navigating) and topological complexity have a far greater and measurable effect on how people navigate in cities than metric distance. They conclude that these effects arise from a cognitive basis as opposed to purely being a mathematical effect of the configuration of the urban grid.

These landmark events and series of papers, distributed over the last fifteen years, represent a slow, steady, yet increasing preoccupation with spatial cognition, by space syntax researchers. This preoccupation seems set to continue: at the next space syntax symposium, it appears, from the preliminary list of papers that the emphasis on spatial cognition is increasing. So where do we go next? And, perhaps more importantly, is this convergence mirrored in any way by the experiences of the cognitive scientists interested in space use and spatial behaviour?

What is spatial cognition?

Spatial cognition research is concerned with the acquisition, organization, utilization, and revision of knowledge about spatial environments. Cognition refers to any of the 'higher-level' brain functions that begin to organize and structure the raw sense data, which represents our 'input' about our surroundings. Recently, 'space' is getting to be a popular academic subject, with a recognition that and understanding of context is vital to the understanding of all types of human behaviour. One way for a lay-person to understand what spatial cognition is about is that it is concerned with how "that stuff out there" (external to us), "gets in here" (is internalized in some

manner). Like in any area of cognitive science, understanding both the underlying cognitive representation formats and the cognitive operations performed on such representations are key issues in spatial cognition. E.g., researchers on 'cognitive mapping' and wayfinding will be interested in both the representational format of spatial information as well as in the mental operations that translate such information into navigation behaviour or map drawing.

Cognitive scientists often have created formal models of wayfinding behaviour that allow larger structures and patterns to emerge. Other cognitive science researchers measure reaction time to investigate information processing. Space syntax research has developed quantitative descriptors of the topological form of settings that are good predictors of where people will be found walking. Environment and behaviour researchers have developed tools such as sketch maps, think-aloud protocols, and tracking of individuals. There are clear opportunities for synergy. The spatial description tools of space syntax can be applied to the analysis of human movement patterns on the level of aggregate movement data, but also have appeared to be applicable more recently to cognitive phenomena such as the layout of sketch maps (Kim & Penn, 2004) and exploration of wayfinding behavior of individual test participants (e.g., Haq & Zimring, 2003; Conroy Dalton, 2003). The modelling precision of cognitive science can be applied to the real-world settings that environment and behavior researchers study. Although cognitive science researchers tend to be concerned with cognitive processes rather than designing good environments, the greater precision in defining the independent variable that space syntax provides can also be applied to cognitive science.

In recent years, researchers in the cognitive science community have made attempts to utilize space syntax techniques to better understand the relation of cognitive phenomena and properties of the environment. This is most prominently visible in a special issue of Environment & Behavior (Issue 1, 2003), but also in e.g., Wiener and Franz (2005). Yet scepticism is voiced as to how well the phenomena originally captured with space syntax methods for aggregate behavioural data translate to individual cognitive processes. How can the requirements and benefits of spatial cognition and space syntax most adequately be brought together?

Areas of overlap

To claim that there is a strong degree of overlap between space syntax and spatial cognition would be erroneous, as there are many examples on either side of the academic fence that would be of little or no interest to the other, for example 'spatial genotypes' in space syntax (of little interest to the spatial cognitive scientist) or, conversely, space and verbal memory tasks (of little interest to the space syntax researcher) to name but a few. However, although the areas of overlap may not be broad, I would argue that they are frequently highly pertinent and, indeed, central to both fields. In the next section we will discuss some of the areas of overlap that were raised at the workshop, through the medium of the papers presented on the day.

The workshop began with our keynote speaker, Professor Bill Hillier, presenting a paper entitled, *Studying Cities to Learn about Minds: how geometric intuitions shape*

urban space and make it work. In this paper, Hiller argues that by examining the products of human creativity, we can understand a significant amount about the way that the human mind works, and, in particular, our cognition of space. This is quite a new approach to spatial cognition, and one that has yet to be approached from within the cognitive science community. The case that Hillier uses as an example for this paper is the city. What particularly seems to intrigue Hillier is that fact that the inhabitants of a city appear to try to impose a geometric order upon the city, which, in many cases, it does not intrinsically posses. He goes on to argue that all cities are pervasively ordered by our geometric intuition, so that neither the forms of the cities nor their functioning can be understood without insight into their distinctive and pervasive emergent geometrical forms.

Hillier's theme of inhabitants' perception of the built environment, at the scale of the cityscape, was further developed by Mavridou, in her excellent paper, *Perception of Architectural and Urban Scale in an Immersive Virtual Environment*. In this paper, Mavridou presents the results of a series of experiments, which have been conducted within a virtual environment. Essentially she takes a pair of similar, theoretic, urban-like environments (superficially similar, yet configurationally quite different) and alters specific variables (for example building heights) that can be held to be associated with urban scale. She then performs a set of qualitative experiments, designed to assess the subject's perceptions of scale within these environments. As a result of this study, Mavridou creates a hypothesis for the perception of urban scale, namely that the perception of form affects the perception of both geometrical and topological properties of space. Her paper culminates in a new definition of scale, which focuses on the relation of form to space.

A virtual reality, urban simulation was also put to effective use in the paper *From Isovists via Mental Representations to Behaviour: first steps toward closing the causal chain* by Meilinger, Franz and Bülthoff. In this paper, the authors present a collaborative research project of behavioural scientists and a trained architect, Gerald Franz. The study investigates the role of spatial properties for the task of learning a route in a complex urban setting. It is performed in a highly detailed Virtual Reality model of the old-town of Tübingen. The authors present convincing evidence that isovist measures capture spatial properties of urban intersection in a manner that is predictive both of human navigation behaviour and its underlying spatial representation.

Staying with both the urban theme and with the use of isovists, Davies, Mora and Peebles take a more practical, problem-directed line of enquiry in their paper, *Isovists for Orientation: can space syntax help us predict directional confusion?* This paper is concerned with the potential problems that people have in orientating themselves in an urban environment, with respect to an accompanying map. The focus of this paper is whether a study of isovist attributes may assist in the identification of spatial orientation problems at specific locations. Again, this paper presents an experiment: in it subjects are required to match a map to a visual (3D) scene and state their perceived orientation. The accuracy and difficulty of this task is measured and then correlated to the spatial attributes of the isovist at that location. The practical goal of this study is to improve maps by adding additional information at those locations found to be problematic.

Maps also feature in the paper, *Architecture of Mind and World: how urban form influences spatial cognition* by Dara-Abrams, which represents another contribution from cognitive science. In this paper the author investigates the nature of systematic distortions typically found in the cognitive maps people form about their spatial environments. These distortions are theoretically tied to heuristics of cognitive simplification. With the help of established spatial judgement and memory tasks, i.e., pointing and map arrangement, Dara-Abrams shows that especially the space syntax measure of integration predicts the degree of mental distortion and may thus provides access to underlying cognitive processes and representations. This paper, in particular, relates very strongly to Hillier's opening paper.

Another practical problem introduced in the workshop, was that of whether urban neighbourhoods have identifiable, spatial characteristics. This was explored by Dalton in his paper, *Configuration and Neighbourhood or is Place Measurable?*. In this paper, the author takes a theoretical rather than experimental approach to the problem by presenting a new method of spatial analysis that Dalton terms, 'point intelligibility mapping'. This takes the concept of 'intelligibility' from Hillier (Hillier, 1996) and takes the radical step of calculating the intelligibility of a point in space rather than an area or district. Dalton's findings are that known and defined neighbourhoods appear to consist of a set of axial lines with similar point intelligibility values, suggesting that the concept of neighbourhood is more than a pure social or cultural construct. Dalton concludes his presentation and paper by illustrating this new method as applied to an area of Boston used by Lynch (Lynch, 1960) in his cognitive mapping experiments.

In one of the few papers concerned with the layout of building interiors, Wineman, Peponis and Conroy Dalton presented their paper, *Exploring, Engaging, Understanding in Museums*. This work was based on a series of observations made of visitors to a pair of travelling science exhibitions. And in particular, they focussed their analysis on patterns of accessibility through the space of the exhibition, connections or separations among spaces or exhibition elements, sequencing and grouping of elements and go on to suggest how these might combine to shape both our perceptions and our understanding of the exhibition content. This paper suggests that these observed patterns of movement form the basis of visitor understanding and that these effects can be deliberately controlled and elaborated through a closer examination of the influence of the visual and perceptual properties of an exhibition.

Another paper that was both concerned with building layout and with the resultant effect on navigation was by Hölscher, Brösamle and Vrachliotis in their paper *Challenges in Multi-level Wayfinding: a case-study with space syntax techniques.* Hölscher et al. reanalyse one of their previous experiments on wayfinding in complex multi-level buildings with the help of space syntax measures. The paper is another example of active collaboration of cognitive researchers with a trained architect, G. Vrachliotis. The authors show that measures like integration and step-depths capture important architectural deficits of the building with respect to its navigability, substantiating earlier qualitative findings. Furthermore, they develop a set of new aggregate spatial measures for routes in a building and link these to human path choice strategies and differences in spatial knowledge.

The final building-level paper presented at the workshop was *Lighting Within the Social Dimension of Space: a case study at the Royal Festival Hall, London* by Antonakaki which investigates the role of light within the social dimension of space

and the influence that lighting may have on visitors' overt behaviour. It attempts to make a link between behavioural, qualitative and configurational issues of the built environment. The author performed an intervention study and was able to show that active variation of the lighting situation in the entrance area of a large theatre, identifying clear changes in the local patterns of movement as well as in visitor interactions. The paper calls attention to the fact that our behaviour in an architectural space is not only determined by its factual geometry, but to an important extent also by the perceptual qualities that can be modulated by adequate lighting design.

The paper *The Ingredients of an Exosomatic Cognitive Map: Isovists, Agents and Axial Lines* by Turner investigates the potential correspondence between the axial map, a key tool in Space Syntax analysis, and the cognitive map as a mental representation of space. The paper combines evidence from a series of experiments with perceptually driven agents inhabiting a simulated space. The paper connects ideas of direct perception and affordances with a notion of a spatial representation that resides outside of the agent itself, hence an *exosomatic* property. From a cognitive science perspective on representational issues this position is clearly controversial and this paper will clearly stimulate the debate about the relative roles of perceptual qualities and spatial memory for human movement in built environments.

Finally, extended abstracts of three poster presentations are included in this volume: Nenci and Troffa presented a poster on *Integrating space Syntax in Wayfinding Analysis*. Based on simulated movement in an urban environment the impact of metric distance on route choice is contrasted with the cognitive costs of choosing different routes through the system. The poster *Wayfinding and Navigation Processes in Piraiki Coast in the City of Piraeus* by Rafailaki compares the spatial memory and orientation of people highly familiar with this coastal area in Greece to visitors of the setting. The author argues that configurational properties of the space help to explain distortions in landmark memory as well as orientation difficulties. The poster *The Role of Space in the Emergence of Conceived Urban Areas* by Yang investigates another facet of the cognitive representation of urban areas: Named areas in a city are a prominent way of representing a complex city in a hierarchy of local regions and the author identifies spatial properties that correspond to the delineation of these urban areas.

It is clear from the descriptions of such a rich variety of papers, that not only are there numerous areas and degrees of overlap between these two groups but that collaborations between cognitive scientists, architects and the space syntax academic community appear to be rather fruitful. It is the hope of all of the workshop organisers that the Bremen 2006 workshop may serve as a springboard for future collaborations. Finally, we would like to take this opportunity to thank all of those who participated in this day, either as presenters or attendees.

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Studying Cities to Learn about Minds

How Geometric Intuitions Shape Urban Space and Make It Work

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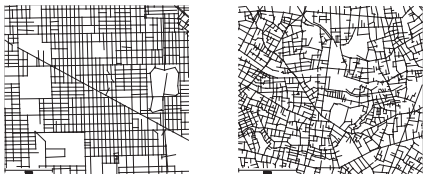
Abstract. What can we learn of the human mind by examining its products? Here it is argued that a great deal can be learned, and that the study of human minds through its creations in the real world could be a promising field of study within the cognitive sciences. The city is a case in point. Since the beginning of cities human ideas about them have been dominated by geometric ideas, and the real history of cities has always oscillated between the geometric and the 'organic'. Set in the context of the suggestion from cognitive neuroscience that we impose more geometric order on the world that it actually possesses, an intriguing question arises: what is the role of geometric intuition in how we understand cities and how we create them? Here we argue that all cities, the organic as well as the geometric, are pervasively ordered by geometric intuition, so that neither the forms of the cities nor their functioning can be understood without insight into their distinctive and pervasive emergent geometrical forms. The city is, as it is often said to be, the creation of economic and social processes, but, it is argued, these processes operate within an envelope of geometric possibility defined by human minds in its interaction with spatial laws that govern the relations between objects and spaces in the ambient world.

Note: I have included only selected images here. All the examples will be shown fully in the presentation.

Introduction: the Ideal and the Organic

The most basic distinction we make about the form of cities is between the ideal and the organic. The ideal are geometric, the organic are not — or seem not to be. The geometric we define in terms of straight lines and 90 or 45 degree angles, the organic in terms of the lack of either (Fig. 1). The ideal seem to be top-down impositions of the human mind, the outcome of reason, often in association with power. We easily grasp their patterns when seen 'all at once'. The organic we take to be the outcome of unplanned bottom up processes reflecting the



(a) Chicago (b) Tokyo

Fig. 1. Sections of the grids of Chicago (left) and Tokyo (right)

practicalities of everyday living rather than the ordering of human minds. We cannot easily grasp their patterns when we see them 'all at once' from above. But, curiously, when we walk about in them, and so see them a bit at a time, the very differentiation of their parts can make them easier to navigate than patterns where parts tend to be similar and in similar relations. From inside, we often find the organic easier to understand, from outside the geometric.

In this presentation I will try to show:

- that the organic city is just as much a geometric product of human minds as the ideal city;
- that the organic city is also shaped by spatial laws which are independent of human minds;
- but which through our geometric intuitions intercede between the processes that create cities and the emergent form of the city itself; and
- that the form-function relation in all cities is driven by their emergent spatial geometry.

First, we must know a little more about the scope of our problem. The relations between organic and geometrical are in fact much more complex than any simple typology. Most cities combine the organic and the geometric in different phases of growth. Rome, for example, like many cities including London, begins organic and grows more geometric as it expands. Tokyo, again like many cities, begins geometric and grows organic. We find cities with bewildering juxtapositions of differently orientated and differently shaped grids, a kind of organic mix of geometric grids. Cities often enclose patches of unplanned settlement as they grow, and of course we also find geometric interventions in organic grids.

Some Consistencies

Cities then seem hugely different in the way in which their grids are put together. It is something of a surprise then to discover that in spite of these differences pretty well all cities share certain common geometric properties. To understand this, we first need to represent urban grids in a consistent way. What we have been looking at so far are *least line maps*, which are probably the simplest representations of urban grids. Let me show how we arrive at them.

First, we take the plan of a town. A piece of computer software called Depthmap, by Alasdair Turner of UCL, then finds all straight lines in the plan that are tangent to pairs of block vertices and extend from them, creating a dense array of lines we call an *all line map*. It describes all possible lines of movement with least distance and fewest turns. Depthmap then by elimination finds the smallest set of lines that cover all the space and make all linear connections from one line to another. We call this the *least line map* of a town plan [1, 2]. It turns out to have some interesting properties, and to allow us to see others.

For example, least line maps for real cities show a remarkable consistency. At all scales, from the local area to the whole city, we find cities are made up of a very small number of long lines and a very large number of short lines, so their line length distributions have *scale-free* properties [3, 4]. This means that wherever we are, we are not far from a line much longer than the one we are on. Formally, it means that these seemingly haphazard growths have acquired some mathematical structure. This poses a puzzle. How can mathematically well-formed networks emerge from decades or centuries of activity by innumerable uncoordinated agents acting in very different social, economic and cultural situations and working with very different geometries?

This is not all we find. If we look carefully at organic grids, we begin to find some geometry [5]. Looking at the least line map of Tokyo in Fig. 1, we intuitively pick out line continuities. What we are seeing are lines joined by nearly straight connections. If we move along one of these we are very likely to find another at the end of the line, and then another. This happens at all scales, but at each scale the lines tend to be locally longer than lines which lack this kind of angular connection. Probabilistically, the longer the line, the more likely it is to end in a nearly straight connection.

We also see a large number of shorter lines with near right angle connections, forming more grid-like local patterns. Again if you find one such line, then it is likely that there will be several others in the immediate neighbourhood. We can also say the shorter the line, the more likely it is to end in a right angle or near right angle. These are the opposite properties to those we find in highly formal cities, like Brasilia or pre-Columbian Teotihuacan, where the longest lines end at right angles on the most important buildings [6].

So organic grids tend to have a kind of fuzzy or probabilistic geometry. They are more regular than they appear at first sight. There is, in effect, a hidden geometry in organic cities: they are quite grid like, in spite of seeming irregular. We can call them *deformed grids*. At the same time, geometric grids are not so regular. Lines are of very different lengths and connectivities, because many are *interrupted*, either by buildings or other artefacts. We can speak of two kinds of grid: *deformed grids* and *interrupted grids*, as in the parts of Chicago and Tokyo shown in Fig. 1 [6].

An Aggregative Law

Let us now focus on the deformed grid of the organic city, where the geometry is not obvious. How do its surprising regularities come about and what do they

mean? Can understanding these help us understand the life of organic cities? We need to know three things:

- First, an *aggregative law* governing the ways in which buildings can be aggregated to create continuous space [7].
- Second, a *spatial law* governing the form of the spatial patterns that emerge from the placing of objects in space in different ways [3].
- Third, a *movement law* we call the *natural movement* which shows how emergent spatial patterns in and of themselves shape movement and co-presence for those inhabiting the space [8].

We will deal with each in turn, beginning with the *aggregative law*.

The basic form of all cities is one of discrete groups of contiguous buildings, or 'blocks', usually outward facing, defining a network of linear spaces linking the buildings. How can this arise?

If we take cell dyads (Fig. 2, top left), representing buildings linked by entrances to a bit of open space, and aggregate them randomly apart from a rule that each dyad joins its bit of open space cell to one already in the system (forbidding vertex joins for the buildings, since no one joins buildings corner to corner), a pattern of buildings and spaces emerges with the topology of a city — outward facing blocks defining a linking network of linear space — but nothing like its geometry, in spite of being constructed on a regular grid [6]. The 'blocks', and so the spaces, are the wrong shape. Where then does the characteristic urban geometry come from?

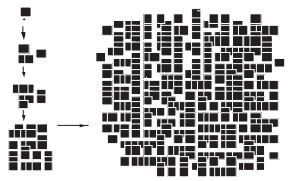


Fig. 2. Aggregating dyads of open and closed cells by a restricted random process

A Spatial Law

This brings us to the second thing we need to know: a *spatial law*. To understand this we need first to think a little about the network of space in cities and how we interact with it. Space in cities is about seeing and moving. We interact with space in cities both through our bodies and our minds. Our bodies interact with the space network through moving about in it, and bodily the city exists for us as a system of *metric distances*. Our minds interact with the city through seeing. By seeing the city we learn to understand it. This is not just a matter of seeing buildings. We also see space, and the city comes to exist for us also as a visually

more or less complex object, with more or less visual steps required to see all parts from all others, and so as a system of *visual distances*.

Distance can then mean more than one thing. But that is not all. Cities are also collective artefacts which bring together and relate very large collections of people. Their critical spatial properties are not just about the relation of one part to another, but of all parts to all others. We need a concept of distance which reflects this. We propose that if *specific distance* means the common notion of distance as the distance, visual or metric, from a to b, that is from an origin to a destination, *universal distance* means the distance from each origin to all possible destinations in the system, and so from all origins to all destinations [6].

Why does this matter? Because universal distance behaves quite differently from the normal metric and geometric concepts of distance that we use habitually (for example Fig. 3).

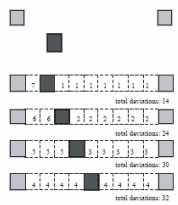


Fig. 3. Moving an object between two others from edge to centre increases the sum of distances from all cells to all others

If we have to place a cell to block direct movement between two cells, the closer we place it to one of the outer cells the less the total distance from each cell to all others because more cell-to-cell trips are direct and do not require deviations around the blocking object.

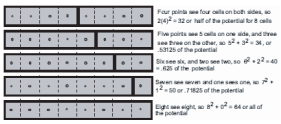


Fig. 4. Moving a partition from centre to edge increases total inter-visibility

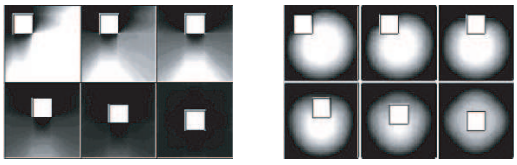
The same applies to intervisibility from all points to all others (Fig. 4). As we move a partition in a line of cells from centre to edge, the total inter-visibilty from each cell to all others increases, though of course the total area remains constant. Both metric and visual effects arise from the simple fact that to measure inter-visibility or inter-accessibility we need to square the numbers of points on either side of the blockage. So all we need to know is that twice the square of a number,

n, will be a smaller number than $(n-1)^2 + (n+1)^2$ [3].

$$2n^2 < (n-1)^2 + (n+1)^2 \tag{1}$$

We can call this the 'squaring law' for space. It applies when, instead of being interested in, say, the distance from a to b, we are interested in the distance, metric or visual, from each point in the system to all others. We called these 'all to all' properties *configurational* [6], and note the difference between these and simple relational or geometric properties. Seen spatially cities are *configurational phenomena*.

So why does this matter? Because how we place and shape physical objects, such as urban blocks, in space, determines the emergent configurational properties of that space, and the spatial configuration of the urban network is, as we will see, fundamental to how cities are formed and how they work. For example, one effect of the squaring law is that as we move objects from centres to edges and then corners in bounded spaces, total inter-visibility in the system increases, as does visual integration (or universal visual distance) defined as how few visual steps we need to link all points to all others (red or light grey means fewer steps) (Fig. 5a). The same applies to metric integration (or metric universal distance) defined as the sum of shortest paths between all pairs of points in the ambient space, which decreases as we move the obstacle from centre to corner (Fig. 5b).



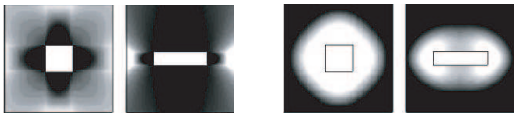
(a) (b)

Fig. 5. Moving an object from corner to centre decreases inter-visibility (a) and increases the mean length of trips (b)

The same is true of shape (Fig. 6): the more we elongate shapes, keeping area constant, the more we decrease inter-visibility and increase trip length in the ambient space. The effect of a long and short boundary is to create greater blockage in the system through the squaring law.

Even at this simple stage, this spatial law has a critical implication for cities: in terms of configurational metrics a short line and a long line are, other things being equal, metrically and visually more efficient in linking the system together than two lines of equal length. (Fig. 7).

Another consequence is for the mean length of trip (or metric integration) from all points to all others in different types of grid, holding ground coverage of blocks, and therefore total travellable distance in the space, constant. In the examples in Fig. 8, dark grey means short mean trip length to other points



(a) (b)

Fig. 6. Changing the shape of an object from square to rectangular decreases intervisibility and increase mean trip length

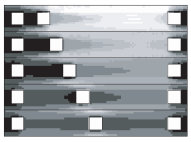


Fig. 7. Other things being equal, a short and long line integrate more than two lines of equal length

through to light grey for longer trips. Compared with the regular orthogonal grid top left, interference in linearity on the right increases mean trip length. But more strikingly, if we reduce the size of central blocks and compensate by increasing the size of peripheral blocks, we reduce mean trip length compared to the regular grid. This of course is the 'grid intensification' that we often note in looking at centre and sub-centres in cities. Again we find a mathematical law underlying an empirical phenomenon [9].

How we place and shape objects in space then determines the emergent configurational properties of that space. But what kind of block placing and shaping make space urban? In Fig. 9a, we aggregate buildings in something like an urban way, with linear relations between spaces, so we can see where we are going as well as where we are. In Fig. 9b we retain the identical blocks but move them slightly to break linear connections between the spaces. If we then analyse metric and visual distances within the two complexes, we find that all to all metric distances (not shown) increases in the right hand case, so trips are on average longer, but the effect is slight compared to the effect on all to all visual distances, which changes dramatically (shown in Fig. 10). Showing visual integration — the visual distance from each point to all others — we see that the left case identifies a kind of main street with side and back streets, so an urban type structure has

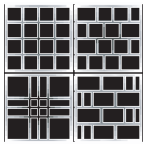
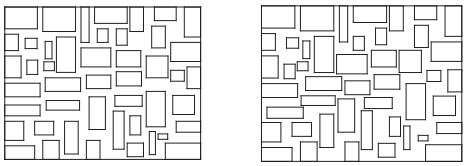


Fig. 8. Changing the structure of a grid changes mean trip length



(a) (b)

Fig. 9. Two slightly different arrangements of the same blocks, with strong linear relations between spaces (a) and weak ones (b)

emerged. But the right case has lost both structure and degree of inter-visibility. Even though the changes are minor, it feels like a labyrinth. We can see where we are but not where we might be.

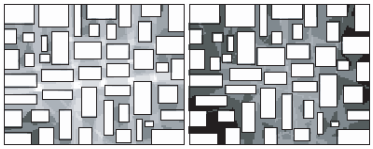


Fig. 10. Visual integration analysis showing how non-urban layout on the right loses both integration and structures through the slight block changes

The effect on computer agents moving around the system is striking, if obvious. In Fig. 11 we move 10000 computer agents with forward vision in the space, again using the software by Turner [2]. The agents randomly select a target within their field of vision, move 3 pixels in that direction, then stop and repeat the process. On the left, the traces of agent movement 'find' the structure of visual integration. On the right, they wander everywhere and tend to get trapped in fatter spaces. This is an effect purely of the configuration, since everything else is identical.

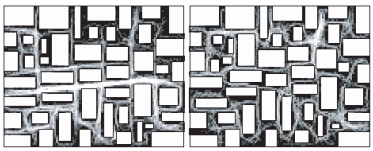


Fig. 11. Traces of 10000 forward looking agents moving nearly randomly

But what about human beings? Human beings do not of course move randomly, but purposefully, and successful navigation in an unfamiliar environment would seem to depend on how good a picture of the whole pattern we can get from seeing it from a succession of points within it. One way we might plausibly measure this property is by correlating the size of the visual field we can see from each point with the visual integration value (its visual distance from all others), so in effect measuring the relation between a *local* property that we can see from each point, and a *non-local* one that we cannot see (Fig. 12). In space syntax we call this the *intelligibility* of the system [6]. The r^2 for the 'intelligible' layout on the left is 0.714 while for the right case it is 0.267.

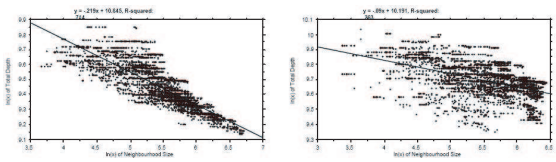


Fig. 12. Intelligibility scattergam for the two layouts in Fig. 9

Defined this way, the intelligibility of a spatial network depends almost entirely on its linear structure. Both field studies [10] and experiments [11] suggest that this does work for humans. For example, Conroy Dalton [11] took a linearised 'urban' type network (Fig. 13 top left) and asked subjects to navigate in a 3D immersive world from left edge to 'town square' and back. As the traces show, they manage to find reasonable routes. But she then moved the (identical) blocks slightly to break the linear structure and reduce intelligibility (Fig. 13 top right), and repeated the experiment. The subjects found the modified layout labyrinthine and many wandered all over the system trying to perform the same way-finding task.

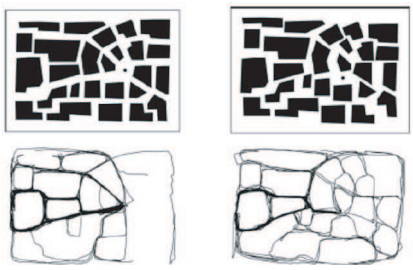


Fig. 13. Trace of human agents an intelligible and unintelligible layout

So if, coming back to our aggregative process, we modify it by requiring those adding cells to the system to avoid blocking a longer local line if they can block a shorter one (Fig. 14 left), we find a much more urban type layout emerges approximating the mix of long and short lines we find in real systems and emulating certain structural features. With the contrary rule — always block long lines (Fig. 14 right) — we construct a labyrinth in which lines are of much more even length. So urban space networks seem to be shaped in some degree by a combination of spatial laws and human agency, with the human agents implementing, and so in a sense knowing, the spatial laws. We suggest that human beings 'know' the configurational laws of space in the same sense that they 'know' the 'intuitive physics' when they throw a ball of paper so that its parabola leads it to land in a waste paper basket.

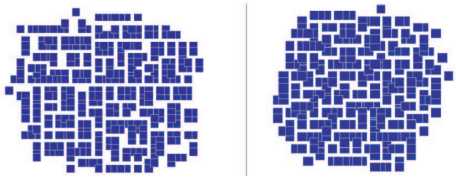


Fig. 14. A layout generated by a 'conserve longer lines' rule (left) and one generated by the inverse rule

A Movement Law

But this cannot be all. Cities are also shaped by economic and social processes. How do these fit into the picture? This is the third thing we need to know. First we can note that the 'urban' type pattern on the left of Fig. 14 is *dual* in the sense that it is composed of a dominant pattern of long lines against a background of areas made up of short lines, approximating what we saw cities to be like. But why this duality? For this we must understand the functional effects of the network, and to understand these we must first learn to analyse the network in terms of what the network is primarily for: that is movement.

Let us first reflect for a moment on human movement. Spatially speaking, every human trip is made up of two elements:

- an origin-destination pair—every trip is from an origin space to a destination space—we can call this the *to-movement* component;
- the spaces passed through on the way from origin to destination—we can call this the *through-movement* component.

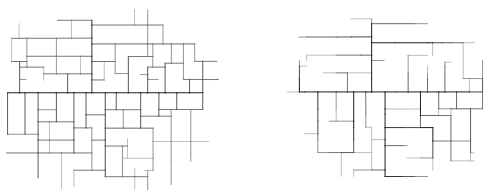
In fact, both of these potentials can be measured:

- *to*-movement is about the *closeness* or *accessibility* of spaces from all others — which is our measure of *integration*: how close is a space to all other spaces [7, 12];

– *through*-movement is about the propensity of spaces to be passed through on the way from all origins to all destination — we call measure of *choice* for a space: how likely is a space to be chosen as part of a route between spaces [10, 12].

Starting from the least line map, we divide each line into its segments (between intersections) and represent the result as a graph. We then assign integration (*closeness* in mathematical parlance) and choice (*betweenness* in maths) measures using shortest path (metric), least angle change (geometric), fewest turns (topological) weightings to relations between each segment and all others, and we apply them at different radii from each segment, also defining radii metrically, geometrically and topologically. This yields a matrix of configurational measures which we can use to see if we can find significant structure-function relations. So we can look at each segment in a system in terms of either its *to*- or *through*-movement potential, defining distance and radius metrically (shortest paths), geometrically (least angle change paths) or topologically fewest turns paths) [12].

Taking the least line map of the left generated system in Fig. 14, we can visualise the pattern of values, which we call the *structure* of the system, by 'colouring up' the network in the usual way for integration (Fig. 15a) and choice (Fig. 15b) without radius restriction. Since integration measures the accessibility of nodes as destinations from origins, then from the principle of distance decay (and other things being equal), we must statistically expect more movement potential for nodes that are closer to all others at some radius. Likewise, since choice measures the sequence of segments we pass through so we must expect a similar bias in real movement. In effect integration measures the *to*-movement, and choice the *through*-movement, potential of spaces.



(a) (b)

Fig. 15. Integration (a) and choice (b) analysis of the least line map of the left generated system of Fig. 14

Natural Movement

Is there a link to real movement? This will depend, among other things, on how people make distance judgements in complex space. So how? Shortest paths?

Fewest turns? Least angle change? We apply the three weightings to the two measures to make six different analyses of the same urban system, and correlate the resulting patterns of values for each segment with observed movement flows on that segment (Table 1,2). If across cases there are consistently better correlations with one or other weighting, then the only logical explanation would be that this weighting reflects better how people are biasing spatial movement choices, since everything else about the system is identical. In fact, across four separate studies in areas of central London, we consistently found that geometric, or least angle weightings yields the strongest movement prediction, with an average of around 0.7 for vehicular movement and 0.6 for pedestrian, closely followed by the topological or fewest turns weighting. Metric shortest paths are markedly inferior in most cases, and in general, *to*-movement potentials are slightly stronger than *through*-movement potentials, though this varies from case to case [12].

This shows configurational factors to do with the network are responsible for a substantial part of movement flows in two senses: the objective *to*- and *through*-movement potentials of the network itself contributes what we might call *network effects* on shaping flows; and these are modified by how human minds contribute *distance effects* through how they read distance in complex spaces. So we have brought to light two rather remarkable things. The first is that the grid configuration itself is largely responsible for the pattern of movement flows along streets. We call this the theory of *natural movement*. Second, the way we navigate spatially is guided not by metric distance as has been uncritically assumed, but by geometrical and topological factors (for a review of the relevant cognitive studies see [12]).

Table 1. Adjusted R^2 values for correlations between vehicular flows and accessibility and choice analyses applying three different weights

Area name	*Gates*	*Measure*	*Least length*	*Least angle*	*Fewest turns*
Barnsbury	116	accessibility	0.131 (60)	0.678 (90)	0.698*(12)
		choice	0.579	0.720*	0.558
Clerkenwell	63	accessibility	0.095 (93)	0.837*(90)	0.819 (69)
		choice	0.585	0.773*	0.695
S. Kensington	87	accessibility	0.175 (93)	0.688 (24)	0.741*(27)
		choice	0.645	0.629	0.649*
Knightsbridge	90	accessibility	0.084 (81)	0.692*(33)	0.642 (27)
		choice	0.475	0.651*	0.580

* Best correlation.

† Numbers in round brackets indicate best radius in segments for accessibility measures.

Table 2. Adjusted R^2 values for correlations between pedestrian flows and accessibility and choice analyses applying three different weights

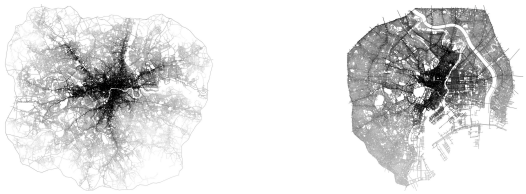
Area name	*Gates*	*Measure*	*Least length*	*Least angle*	*Fewest turns*
Barnsbury	117	accessibility	0.119 (57)	0.719*(18)	0.701 (12)
		choice	0.578	0.705*	0.566
Clerkenwell	63	accessibility	0.061 (102)	0.637 (39)	0.624*(36)
		choice	0.430	0.544*	0.353
S. Kensington	87	accessibility	0.152 (87)	0.523*(21)	0.502 (27)
		choice	0.314	0.457	0.526*
Knightsbridge	90	accessibility	0.111 (81)	0.623*(63)	0.578 (63)
		choice	0.455	0.513	0.516*

* Best correlation.

† Numbers in round brackets indicate best radius in segments for accessibility measures.

The Spatial Form of Cities

With this knowledge, then, we have a new tool for investigating the form and functioning of cities. First let us look at the emergent spatial form of cities. Applying the *integration*, or *to-movement*, measure to real cities, and using the least angle change, or geometrical, definition of distance, we find some remarkable emergent geometrical patterns, and again we find they are near invariant across different kinds of city. For example, we commonly find a pattern we call a *deformed wheel*: a hub, spokes and rim forming the main structure of public space, and the residential areas in the interstices of the wheel. This first came to light in the study of small towns in the South of France, and we found the same pattern in London's urban areas with her 'urban villages' at the hub. But it was something of a surprise to find the pattern approximated in very large cities such as London, with a relatively weak rim, and Tokyo, with much stronger, and multiple rims (Fig. 16).



(a) London (b) Tokyo

Fig. 16. Integration analysis of metropolitan London and Tokyo

We seem to find this pattern emerging under very different geometric conditions. For example, we find this emergent structure in strongly geometrical Atlanta, and the very ungeometrical old city of Hamedan in Iran (Fig. 17).

(a) Atlanta (b) Hamedan, Iran

Fig. 17. Integration analysis of Atlanta and Hamedan showing how the deformed wheel pattern emerges under very different geometrical conditions

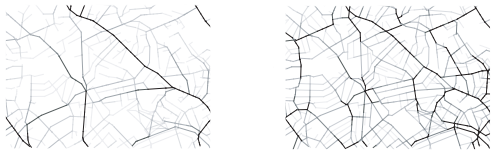
When we apply the *choice*, or *through-movement* measure, we find a different kind of structure reflecting some of the deformed wheel but more like a network (Fig. 18).

(a) London (b) Tokyo

Fig. 18. Choice analysis of London and Tokyo showing the network pattern

Again, this seems to work for interrupted grids as well as for deformed grids. We can also combine the two measures by simply multiplying one by the other, to give a combined picture of the *to*- and *through*-movement potentials of each street segment in the system with respect to all others.

Applying the restricted radius measures then allows us to capture much more detail of local structure, reflecting the fact that when we make large scale trips in the city we tend to use the global structure, but when we move locally we will often find ourselves prioritising spaces which are not part of global pattern, but which are locally important. We can use the colour range as a kind of microscope to explore these detailed local patterns. For example, in Fig. 19, we reduce the



(a) Radius n (b) Radius $1000m$

Fig. 19. showing radius n and radius $1000m$ choice analysis of part of north west London

radius of the choice measure from n (left) to 1000 metres (right) in an area of north west London, and then use the colour range to zoom in and begin to detect the urban villages, which of course are focuses of local, but not global, movement.

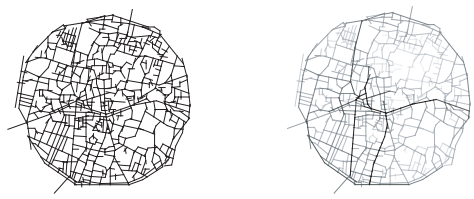
We can use the same technique to detect London's often surprising pattern of local shopping street and market areas, and to identify local area structures, often in the form of a local deformed wheel. The local deformed wheel is in fact the secret of London's surprisingly strong local organization and the reason we name it as a system of 'urban villages'.

But how do these patterns affect the functioning of the city? We already know the emergent structure of the grid reflect and shape movement flows. Does this have further consequences? It does, and by understanding these consequences we arrive at a new theoretical definition of the city. What we find is that the link between the network configuration and movement flows is the key to the dynamics and evolution of the system. Because the network shapes movement, it also over time shapes land use patterns, in that movement-seeking land uses, such as retail, migrate to locations which the network has made movement-rich while others, such as residence, tend to stay at movement-poor locations. This creates multiplier and feedback effects through which the city acquires its universal dual form as a foreground network of linked centres and sub-centres at all scales set into a background network of residential space. This is the space syntax definition of a city. Through its impact on movement, the network has set in train a self-organising processes by which collections of buildings become living cities. In terms of how we should model cities, network configuration has shaped the pattern of differential attraction, that characterises all cities. So configuration, not attraction, is primary.

The Dual City

We have then found our dual structure, and we can explain it. The foreground structure, the network of linked centres, has emerged to maximise grid-induced movement, driven by micro-economic activity. Micro-economic activity takes a universal spatial form and this type of foreground pattern is a near-universal in self-organised cities. The residential background network is configured to restrain

and structure movement in the image of a particular culture, and so tends to be culturally idiosyncratic, often expressed through a different geometry which makes the city as a whole look spatially different. We call the first the *generative* use of space since it aims to generate co-presence and make new things happen, and the second *conservative* since it aims to use space to reinforce existing features of society. In effect, the dual structure has arisen through different effects of the same laws governing the emergence of grid structure and its functional effects. In the foreground space is more random, in the background more rule-governed, so with more conceptual intervention.



(a) (b)

Fig. 20. The old city of Nicosia (left) and its integration analysis, showing the deformed wheel core in spite of culturally differentiated residential space

We can illustrate this most clearly in a city with more than one culture (now unfortunately separated): Nicosia (Fig. 20). Top right is the Turkish quarter, bottom left the Greek quarter. Their line geometry is different. In the Turkish quarter, lines are shorter, their angles of incidence have a different range, and there is much less tendency for lines to pass through each other. Syntactically, the Turkish area is much less integrated than the Greek area. We can also show that it is less intelligible, and has less synergy between the local and global aspects of space.Yet in spite of these strong cultural differences in the tissue of space, we still find Nicosia as a whole is held together by a clear deformed wheel structure. This shows how micro-economic activity spatialises itself in a universal way to maximise movement and co-presence, while residence tends to reflect the spatial dimension of a particular culture, and the expression is in the first instance geometrical. Since residence is most of what cities are, this 'cultural geometry' tends to dominate our spatial impressions of cities.

A Cognitive Conjecture: How Do We Acquire Non-local Knowledge of the City?

But whatever their geometry, the space networks have further unexpected property. Although the form of the system has evolved bottom-up, its functioning is top-down, in that the movement flows which drive the evolution of the system reflect the position of each space in the large scale configuration, not the local

properties of the space. In this sense, the properties of spaces which are critical to its functioning are *non-local* and reflect a large number of remote connections. This poses a very interesting question. In order to produce the patterns of flows we find, people must be using some kind of non-local internal representation of the space network, with both geometrical and topological properties. Since people see cities only a bit at a time, it seems that they somehow *synchronise* discrete experiences into a *non-local* picture. What might this be like?

In space syntax, non-local patterns are visualised through a graphical device we call the *justified graph*, or *j-graph* [6]. We illustrate this through Fig. 21. Each element in the system — in the case in Fig. 21 each 'street' — is represented as the root of a graph with all other elements to which it connects aligned in the first layer above, those that connect to this layer in a second layer, and so on. In this way we can picture, for example, the complexity of routes from each street to all others, a critical non-local property. A graph shallow from the root, that is an *integrated* j-graph, means little route complexity to all other lines, a graph deep from the root much complexity.

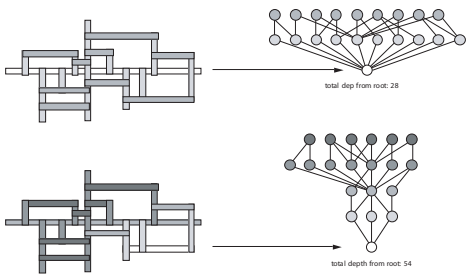


Fig. 21. A notional grid and two of its justified graphs

The representation people are using for navigation looks as though it might be some kind of justified map of connected lines: a *justified line graph*, perhaps. What might cognitive science say about this? First it says of course that human beings have *egocentric* route knowledge and *allocentric* map knowledge [13]. It is the latter we need to solve navigational problems. But cognitive science also says something else very interesting. In memory people routinely correct bends to lines, and near right angles to right angles (for example, [14]). These are instances of what we might call the *Kantian simplification*: people impose more geometry on the situation than it actually has. But in terms of our putative line graph, correcting lines is not so much a geometrical error as a topological simplification. Its effect is to *turn two line elements into one* and so simplify the line topology. It also eliminates an asymmetric relation by which we must go through this space to get to that one, so making the j-graph shallower.

We might then conjecture that going from route knowledge to map knowledge is a matter of going *from the j-graph* (in fact its spanning tree) *to the graph*. The Kantian simplification may be part of the means by which we pass from an

egocentric to an allocentric understanding of space. The Kantian simplification makes the topo-geometric j-graph simpler and less asymmetric. The more we straighten lines and correct turns, the more the graph become shallow from its root, symmetric and bipartite. This makes the line graph easier to transform to see other viewpoints, and it is perhaps this transformability that permits the passage from an egocentric to an allocentric model. Could this be how we learn cities?

Further Cognitive Reflections on the Objective City

Two further aspects of this account of cities stand out as challenging our cognitive paradigms. Both reflect the fact that the city and its functioning, as we have descried them, are products of human agency, and inconceivable without the active role of human cognition. The first is that the complex emergent patterns and processes we have described as near-invariant in the form and functioning of cities are constructed from the metric and geometric properties of the system of linear spaces that links the city into a single system in the first place, that is the lengths of lines and the angles of incidence at the intersections between lines. The line-graphs which have been the basis of our analysis are composed essentially of no more than this.

We find, in effect, that the city has a pervasive two level geometry. There is a geometrical consistency in the way in which the relations between line lengths and angles of incidence at the intersection are formed into local patterns to give the local differentiation between the more public and more residential parts of the system. And there is a geometrical consistency in the way in which these patterns are scaled up to give the emergent structure of the whole city. It is these geometrical consistencies that govern the form-function relation in cities and which relate the spatial patterning of the city with the emergent spatial patterning of city life. The city cannot have acquired the pervasive *geometricity* of its form without the equally pervasive involvement of human geometric intuition. In this sense, human geometric intuitions seem *embedded* in the city itself.

Second, we have also described a system in which *spatial laws*, implemented through human agency, intervene between the patterns of micro-economic and social activity that animate the city, and the emergent spatial form of the city itself. We have no concept for such a *human-mediated but law-governed* system. But what is clear is that the relation between human activity and space is mediated by spatial laws, and it is only through the lawfulness of space that economic and social activity is able to express itself in space. On reflection, it must be that way.

An unavoidable consequence of this is that cities are generic cognitive — and so human — objects before they are economic and social objects. Paradoxically, it is because they are so that they can absorb, without strain, massive changes in the patterns of activity that animate them. The relation between the form of the city and its functioning is in effect *generic* not specific. It is not specific patterns

of activity that shape space but the way in which the relation between space and activity is mediated by the need for movement and co-presence. New patterns of activity, like the old, will require the full continuum of spaces, from integrated to segregated, and so will discover how to fit into and perhaps modify slightly an existing urban pattern. This *capaciousness* of the city for the absorption of new functional patterns comes from the underlying form of the city, that is the *generic cognitive* city, and its priority over the social and economic city.

A General Mechanism: Description Retrieval?

The *signs of minds* that we detect in the city, then, suggest the pervasive involvement of both geometric intuitions and spatial laws in both the formation of the city and its functioning. Is there a general mechanism governing this link? Here it is proposed that there is, and that it depends on the proposition that our mental interaction with the spatial world engages abstract relational ideas as well as concrete elements. In general, spatial relations are ideas with think *with* rather than *of* [6]. The classic case is the *prepositions*, like *between* or *beyond* all of which embody bundles of relations in abstract form, and we use them routinely to structure our picture of the world. We propose there is a generic mechanism we call *description* retrieval [7] through which we extract abstract information from concrete events and re-embody it in real time.

Suppose, for example, one person builds a house and another person builds a house next to it (Fig. 22a-b). In one case subsequent builders ignore the first relation (the top left-right sequence) and create a random pattern, in another (the bottom left-right sequence) other builders 'get the idea' of the initial relation and re-embody it in subsequent actions, and a regular form emerges.

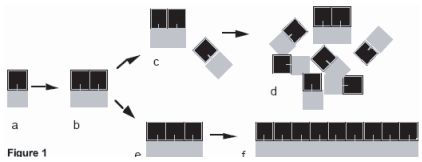


Fig. 22. The generation of simple forms from simple rules

This process is interesting at two levels: that of the process and that of the emergent form. The relation 'next to' has an interesting abstract property: it is *symmetrical*, in that if a is next to b then b is next to a, unlike, for example, *above* or *below*, or *behind* and *in front* which are *asymmetrical*. In reproducing the relation, then, builders are reproducing the abstraction, and in this sense emulating a rule following behaviour. We can think of this as a kind of *embedded rule*: the rule is inherent in the concrete behaviour. Human behaviour is full of embedded rules of this kind, and often what is embedded is an abstract scheme

of spatial relations. It is hard to avoid the inference that we routinely interact intuitively with the abstract spatial schemes in the real world.

The emergent forms (Fig. 22, on the right) are also interesting. In the regular case, where the rule-following has put similar things in similar relations, we easily retrieve a description of the high level object as a line or perhaps 'terrace', but in the random case we do not. In the regular case, it seems we are able to *synchronise* the discrete objects into an overall shape to create a higher level *template* for further embodiment. In the other we cannot. In general this seems to be the case.

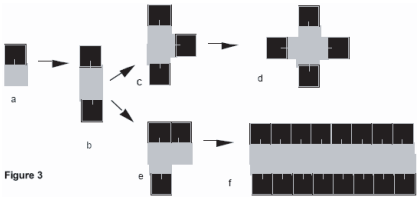


Fig. 23. Other simply generated forms

By following two embedded rules rather than one (Fig. 23), we find other cases where local rule-following leads to the emergence of other regular global forms, one we would name a *courtyard*, the other a *street*. In fact, the basic forms for which we have names can all be seen as products of a local rule-following leading to global forms in which *similar things are put into similar relations*.

But exactly what is it that we recognise at this *template* level? Is this just the *recursion process* of locally similar events? Or is the *upper level* recognition in some sense independent of the lower level? The cases in Fig. 24, in which the same objects are re-arranged left to right to allow more global linear connections, provide the answer: the upper level is *independent* of the lower level. The left figure is no less recursive than the right figure, but we see it only as a recursive local pattern, not as a whole. The centre one we are more or less able to synchronise as a whole because lines have appeared at the level of the whole. With the one on the right, we are far more aware of the global pattern that of any recursive process. We have a kind of *global takeover* and we retrieve an upper level *template*.

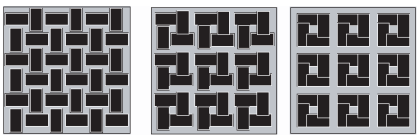


Fig. 24. By increasing the linear organization from left to right we move from retrieving a local to a global description

So the process of *synchronisation* the upper level of the *description retrieval* process seems to require certain formal properties to be satisfied at that level, and will not happen without those properties. We begin to see why the emergent spatial complexity of the city *requires* a certain *emergent geometry* if human beings are to interact with it effectively.

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Exploring, Engaging, Understanding in Museums

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Abstract. Patterns of accessibility through the space of the exhibition, connections or separations among spaces or exhibition elements, sequencing and grouping of elements, form our perceptions and shape our understanding. Through a review of several previous studies and the presentation of new work, this paper suggests that these patterns of movement form the basis of visitor understanding and that these effects can be deliberately controlled and elaborated through a closer examination of the influence of the visual and perceptual properties of an exhibition. Furthermore, it is argued that there is also a spatial discourse based on patterns of access and visibility that flows in its own right, although not entirely separate from the curatorial narrative.

Keywords: museum, spatial layout, visitor movement and visibility.

1 Introduction

In museums the educational message is constructed through movement in space. Patterns of accessibility through the space of the exhibition, connections or separations among spaces or exhibition elements, sequencing and grouping of elements, form our perceptions and shape our understanding. These effects may be much more subtle than the influence of the content or design of the exhibition elements themselves; however, this 'probabilistic' pattern of movement in space forms the basis of visitor understanding. Furthermore, it is suggested that these effects can be deliberately controlled and elaborated through a closer examination of the influence of the visual and perceptual properties of an exhibition so that exhibition design is based upon a more complete understanding of the effects of space on visitor experience.

As visitors move through the museum and through its exhibition spaces, experience unfolds based on the content and sequencing of exhibitions and exhibition elements. What becomes clear from this investigation is that there is also a spatial discourse based on patterns of access and visibility that flows it its own right, although not entirely separate from the curatorial narrative.

2 Space Syntax Analysis

One of the limitations of previous research exploring the effects of spatial layout on visitor movement patterns has been the lack of rigorous tools for assessing characteristics of spatial configuration. The studies reviewed and the study reported in this paper employ systematic methods of describing the overall configuration of the museum setting. These methods primarily derive from the theory and methods of space syntax developed by Hillier et al. at the University College London (Hillier and Hanson, 1984, Hillier, 1996; Peponis and Wineman, 2002).

The techniques for the analysis of spatial form or "space syntax analysis" characterize spatial systems on the basis of the ways in which spaces are related to other spaces within a larger system, rather than through the more traditional characterization of metric distance. Syntactically a system of spaces is more "integrated" if spaces can be easily reached from one another, or more "segregated" if one must travel through many other spaces to move from one space to another.

Syntax analysis techniques can be applied to two dimensional building plans or urban layouts to produce quantitative measures of the characteristics of spatial layout. The analysis represents a spatial system as a series of smaller spatial units or as a system of lines of potential movement between these spatial units. For each of these representations, syntax analysis involves the study of patterns of connections, both in terms of the relationship of each spatial unit or line to its immediate neighbors measured by variables such as "connectivity," and by the relationship of each spatial unit or line to the entire set of lines that constitute the spatial system being studied, measured in terms of "integration".

The spatial units for syntactic analysis can also be based on visibility polygons or isovists. The term visibility polygon is used in a mathematical sense: a visibility polygon covers all points that can be linked to a given root-point by a visibility line that is not interrupted by any boundary. When visibility polygons, or isovists, are drawn at eye level, they capture the objective properties of the visual field as structured by the affordances of environment (Gibson, 1979). When they are drawn at floor level, they capture the objective properties of environment affecting movement. In space syntax, layouts are studied according to the pattern of intersection of visibility polygons, so that each position is described not only according to the properties of its own visibility polygon, but also according to the visibility thresholds that are involved in its relationship to all other positions in the layout. Software is used to flood-fill all navigable space within the area of study with a grid of vantage points, and to generate visibility (eye level isovists) or accessibility (floor level isovists) polygons from each of these locations. Each of these polygons generated from the grid of vantage points can be characterized by a series of properties including area, perimeter, minimum, mean, and maximum radial length, and so forth. Once the grid polygons have been calculated, we can examine the relationship between each polygon generating point and every other generating point to develop a set of 'syntactic' measures (including "connectivity" and "integration").

It is suggested that a layout is more understandable and predictable if one can glean the structure of the global system on the basis of the structure of the local area. Thus, "intelligibility" is defined as the correlation between local measures (such as

connectivity) and global measures (such as integration). In museums, the intelligibility of space is intertwined with the manner in which space becomes accessible to exploration and the contents become available to search.

3 Patterns of Accessibility/Visibility and Visitor Movement

Tversky (2003), in her work on mental mapping, describes cognitive representations of large-scale space as constructed of elements (landmarks, paths, links, and nodes) that are held within an 'encompassing frame of reference'. She suggests that the experience of three-dimensional space can be schematized as a two dimensional representation in which systematic errors of judgment are introduced to maintain the overall reference frame. Kuipers and his associates (2003) reiterate this notion of the framework in navigational paths. The authors found that expert wayfinders exploring a complex environment soon ‘discover’ a small set of major paths (what Kuipers has termed the ‘skeleton’ in the cognitive map) that are then used to access neighborhood areas and ultimately destinations. These skeleton paths are those rich in links to other paths and destinations (similar to those paths that would be identified in syntax analysis as most integrated). In Kuipers’ work, computational simulation to test this hypothesis of spatial navigation found that the greater the number of links to other destinations, the greater the likelihood of path usage (for paths of equal topological efficiency). Echoing Tversky's concept of the reference frame, this 'skeleton' of routes becomes more heavily used than others in the spatial system. In the Peponis et al. study (1990) of a geriatric facility, visitors unfamiliar with the facility were asked to explore freely to gain an understanding of spatial layout. Visitors were found to rapidly discern and follow routes that provided access to multiple destinations (more integrated routes).

This is similar to the exploratory behavior of other species. Ants, for example, that scout daily foraging paths begin their search with a wide array of random search trails at first, but soon consolidate these routes to a smaller series of primary access routes (a linear skeleton) which then fans out in prime foraging areas (see Gordon, 1999, p. 34; Camazine, 2001). If we consider complex systems theory, this pattern of widely arrayed trails quickly merging into a limited framework is an effective strategy to search a complex environment (Johnson, 2005).

These search patterns appear to be similar to visitor exploration in museums. As visitors explore museum space, they begin to follow a 'skeleton' of primary paths that link to multiple neighborhoods of destinations and can be defined in syntactic terms as more integrated paths of access and visibility based on global spatial characteristics of the museum. These paths lead to local exhibition 'neighborhoods' where movement becomes dependent upon local characteristics of exhibit visibility and accessibility.

Several studies underscore the strength of spatial configuration in defining exploratory paths. Studies of visitor movement in the Tate Gallery in the U.K. (Hillier et al., 1996; Turner and Penn, 1999; Turner et al., 2001) and a study of eight complex art museums in the U.S. (Choi, 1999) report the effects of spatial layout on both visitors’ movement through spaces in the gallery and the number of people observed standing in rooms (occupancy rates). These studies confirm that, in museum settings

that offer opportunities for movement choice, patterns of visibility and accessibility are more powerful predictors of movement than either metric measures (for example, Euclidean shortest path lengths) or characteristics of the exhibit elements.

Furthermore, Choi noted that in museums with greater numbers of spaces (irrespective of the sizes of those spaces), and/or those that have more route choices, visitor itineraries were more selective, not exhausting the entire collection. As a consequence, individual spaces were less evenly visited. Choi also found that visitor viewing paths were more varied in museums with spatial layouts that were more highly integrated (spaces are easily accessible from all other spaces) and more intelligible (spatial characteristics at the local level were similar to those at the global level); however, in these museums, although individual visitor paths were more varied, museum spaces overall were visited more evenly. Therefore, Choi concluded that intelligibility and integration encourage more individual itineraries; yet these spatial qualities also result in more balanced viewing of spaces across the population of visitors. This suggests that when visitors have the opportunity to construct their own itineraries, in museums where the spatial layout offers choice but is accessible and predictable, the sum of their unique viewing paths will cover a broad array of the museum spaces.

Visitor activity in museums can be characterized as both movement through space, exploration on a more global scale (as discussed above), and static occupation of space, such as stopping at exhibit elements. The effect of space in predicting where visitors were likely to stop or spend more time is more complex. Choi (1999) found that the configuration of space in and of itself did not generate or structure the number of visitors occupying a space at any point in time. However, results of his study suggest that visitors tend to stop in spaces from which more people are visible. Thus, visitors stop more often in spaces that have greater visual connections to other spaces; they also stop in spaces that are visually connected to the more integrated spaces of the museum (the spaces most used by *moving* visitors). In this way the awareness of people in the museum is structured by spatial patterns of visibility and accessibility. Built form becomes instrumental in structuring the awareness of others, and in this way creating a sense of community based on visual encounter.

4 Patterns of Accessibility/Visibility within Open Plan Exhibition Space

In contrast to the previous studies that focused on exploratory movement patterns through space, we present a comparative study of relatively simple open-plan science exhibitions that explores movement within a single open space, and describes layout as a spatial pattern of visibility and accessibility arising from the distribution of objects in space. First we discuss how exploratory movement, visual contact and active engagement with individual exhibits are affected by these simple spatial variables. Then we discuss the effects of more complex spatial variables that take into account the spatial grouping and visual coordination of exhibits according to conceptual themes. This allows us to discuss how observed patterns of behavior may reflect not only simple perceptual information regarding the patterns of visibility and

permeability afforded by an exhibition setting, but also more complex perceptual information that relates to the cognitive content of exhibits.

Our study focused on two traveling science exhibitions created by Carnegie Science Center, each evaluated in two different settings. 'Robotics' introduced principles that govern robotic design and function, and traveled to the Great Lakes Science Center (Cleveland) and to the Carnegie Science Center (Pittsburgh). The second exhibition, “ZAP surgery”, presented new technologies for medical operations, and was studied at The Tech museum in San Jose and at the Great Lakes Science Center in Cleveland. All four sites were moderately sized open plans that offered almost random sequences of movement and relatively unobstructed visibility.

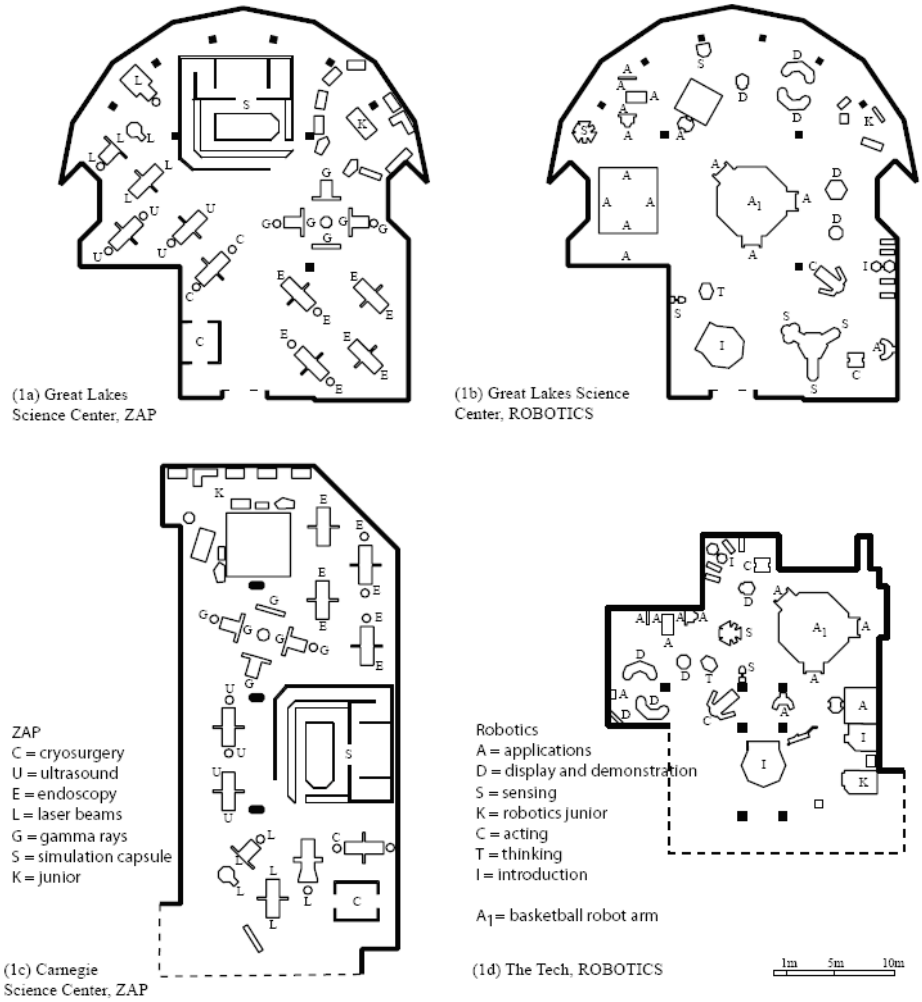

Fig. 1. Diagrammatic plans of two science exhibitions in different settings

The advantage of studying traveling exhibitions results from the spatial variability across settings. For each exhibit element, although the content and visual attraction remained constant as the exhibition is adapted to a new setting, measures of our spatial variables change. This allowed us to examine the effects of spatial variables on visitor behavior patterns above and beyond the effects of element content or presentation.Individual exhibit elements provided self-contained information; however, they were also classified according to conceptual themes. For example in the Zap exhibition, elements were visually coordinated and spatially grouped according to the following themes: gamma rays, laser beams, cryosurgery, endoscopy, and ultrasound. In the case of Robotics, the presentation of exhibits referred to aspects of acting, sensing, areas of application, demonstration of use, and exhibits aimed at "junior" visitors (see figure 1 for the spatial distribution of exhibits by theme). The conceptual themes were made more evident visually in the ZAP exhibition; in Robotics, conceptual themes were less strongly suggested, either by spatial grouping or through visual design. In both instances, however, the classification of individual exhibit elements by themes was objectively documented in the literature accompanying the exhibitions, whether in printed catalogues or webpages.

The temporary exhibition area itself varied from the relatively compact and clearly bounded shape of the Great Lakes Science Center, to the more elongated shape of the Carnegie Center, or the more compact but weakly bounded space at The Tech. The few large individual exhibit elements, such as the ZAP Cam Simulation Capsule in the ZAP exhibition (label S, figure 1a and 1c), or the Basketball Robot Arm in the Robotics exhibition (label A_1, figure 1b and 1d), tended to be so located as to divide space while at the same time acting as focal points of visual attention. There was ample cross visibility between individual exhibits. The arrangement allowed for maximum choice of exploration paths, as there were relatively few impediments to movement.

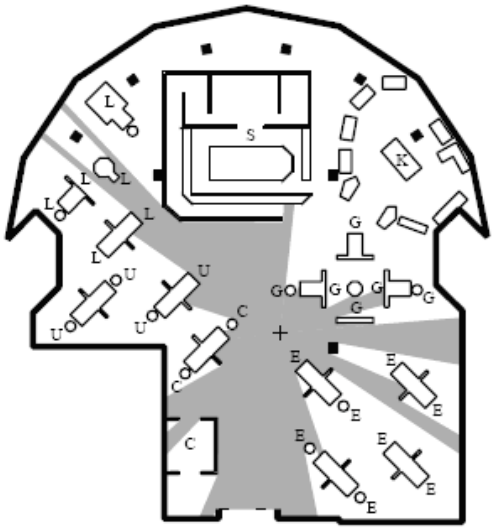

Fig. 2. Example of a projection polygon.

Behavioral descriptors. Behavioral data were collected by direct observation in the field. About one hundred randomly selected visitors were unobtrusively tracked in each setting and their paths recorded on diagrammatic plans. When a visitor path came sufficiently close to an individual exhibit, such that full awareness of the visual contents of the individual exhibit was possible, and indeed most likely, a *contact* was said to occur. When a visitor stopped at an individual exhibit element, whether to physically interact with it or to study its visual content, an *engagement* was registered. Contacts include engagements but not all contacts involve engagement. Repeat contacts and repeat engagements were also registered. Each individual exhibit was thus assigned its corresponding "1st Contact", "1st Engagement", "Repeat Contact" and "Repeat Engagement" counts. Repeat counts include the 1st occurrence of the relevant behavior. In the rest of this paper, these counts will be the behavioral performance scores assigned to individual exhibit elements. Table 1 provides a basic quantitative profile of visitor behavior. Visitors spent a total of between 16 and 23 minutes per exhibition, depending on the setting. Each individual exhibit element was contacted by between 46% and 59% and engaged by between 13% and 24% of the total number of visitors, also depending on the setting.

Table 1. Quantitative profile of visitor behavior in four exhibition settings.

	ZAP! Surgery Great Lake Science Center	ZAP! Surgery Carnegie Science Center	Robotics Great Lakes Science Center	Robotics San Jose Tech Museum
Number of visitors tracked	96	97	103	102
Avg. total time per visitor (minutes)	22.7	15.9	21.1	16.6
Avg. total stop time per visitor (minutes)	18.8	12.5	17.4	12.8
Avg. # of contacts per visitor	28.26	23.80	32.10	23.11
Avg. # 1st contacts per individual exhibit	48.74	44.44	57.71	60.60
% visitors contacting each individual exhibit	51%	46%	56%	59%
Avg. # repeat contacts per individual exhibit	92.52	80.78	100.68	98.04
Avg. # of engagements per visitor	10.38	6.03	12.51	9.82
Avg. # 1st engagements per individual exhibit	19.93	13.00	24.74	24.40
% visitors engaging each individual exhibit	21%	13%	24%	.24%
Avg. # repeat engagements Per individual exhibit	31.78	17.63	38.55	36.88

In order to determine the attraction exercised by individual exhibit elements, individual visitor paths were first described according to the sequence of contacts, including engagements, and also according to the sequence of engagements only. For example, the string of numbers {3, 2, 1, 4, 8, 12, 13, 36, 37, 35, 23, 1, 3, 2, 19} describes a visitor's path as a sequence of contacts where each number stands for an

individual exhibit; the string of numbers describing the same visitors' engagements is much shorter: {3, 36, 3}; the first string, transcribed according to themes becomes a string of characters: {C, C, C, U, L, L, L, S, K, G, G, C, C, C, E} (exhibits 3,2,1 belong to the same theme C, exhibit 4 belongs to theme U and so on), while the second becomes {C, S, C}. The *strings according to individual exhibit elements* and the *strings according to themes* were the basis for computing the appropriate behavioral attraction scores for each individual exhibit, either based on *contacts* (including engagements) or on *engagements* only. Individual visitors are also characterized by the total time they spent in the exhibition. In the next section we will discuss how contact and engagement scores associated with individual exhibit elements are affected by simple spatial variables.

Spatial descriptors. Two kinds of spatial layout descriptors were applied, those pertaining to the relative accessibility of individual exhibit elements and those pertaining to their cross-visibility. Accessibility was measured based on the analysis of visibility polygons (drawn at floor level). Here, the Area of a projection polygon (figure 3) measures the amount of space from which the vantage point is directly accessible along an uninterrupted straight line. The indirect accessibility of each position from other positions is described according to the pattern of intersection of projection polygons. When two polygons intersect, any point on one that does not lie on their intersection is one direction change away from the vantage point of the other. Accordingly, the directional distance (number of required direction changes) of a point from any other point can be expressed as a function of the minimum number of sequentially intersecting projection polygons that must be used to move from one position to the other. Consistent with other studies, we will use the term "Mean Depth" (Hillier and Hanson, 1984) to describe the directional distance from any point taken as a vantage point of a projection polygon to all other points also taken as vantage points of projection polygons.

$$MD_{(i)} = \sum_{\substack{j=1 \\ j \neq i}}^{k} d(i-j) \qquad \textbf{(1)}$$

$MD_{(i)}$ is the Mean Depth from vantage point i
$d(i\text{-}j)$ is the number of intervening polygons between vantage points i and j
k is the number of vantage points in the system

"Area" and "Mean Depth" values were computed using "Omnivista" software written by Dalton and Conroy-Dalton. Omnivista flood-fills all navigable space within each of the exhibition sites with a grid of vantage points, and generates projection polygons from these locations. Various properties are then computed for each polygon; however, "Area" and "Mean Depth" proved to have greatest relevance to our research. Average Area and Mean Depth values were computed for each individual exhibit element contact region (the region where visitors must stand in order to engage the exhibit element), taking all the vantage points encompassed by the region into account. The grid used to flood-fill space is 30cm by 30cm and so each contact region encompassed several, or even many, grid units. Figure 3a shows a

layout shaded according to the area of projection polygons drawn from each square of the 30cm by 30 cm grid. Likewise, figure 3b shows the same layout shaded according to the mean depth of the polygons.

Particularly in open plan exhibition space, it may be easy for visitors interacting with one exhibition element to see other elements. These opportunities would be revealed through analysis of projection polygons (taken at eye level). However, it is also characteristic of open plan exhibitions that one may see other exhibition elements, but perhaps only partially. The primary façade or contact area may be obscured. Our interest in looking at visibility patterns was the extent to which visitors at one exhibit element could see the contact area of another element.

Rather than all of the exhibit elements that might fall within a viewing area (projection polygon), we were interested in a graph analysis indicating the contact areas of other exhibition elements that might be viewed either fully or partially. Furthermore, in situations such as those where exhibit elements are oriented front to back, it may be that a visitor can view the contact region of another exhibit element, but someone at that location cannot see the 'face' of the other. To represent this cross-visibility between exhibit elements we used directed graphs, whose nodes represent individual exhibit contact regions, and whose arcs describe the visibility of one position from another. These graphs were established empirically, in the field, since the visibility of the contact face of an exhibit from the contact region of another exhibit depends on the precise details of a layout that are not available with the current automated systems. Clearly cross-visibility differs from cross accessibility in that the contact face of one exhibit element could be fully visible from the contact region of another, even when movement between the two exhibits would be hindered by the presence of intervening exhibits. One directed graph was used for Full Visibility and another for Partial Visibility. "Full Visibility" was defined as being able to see another exhibit element so as to determine its nature and contents. "Partial Visibility" was defined as being able to see enough information to determine the presence of another exhibit element, but not its contents or its nature. Thus, the "Full Visibility" graph is a subset of the "Partial Visibility" graph.

Cross Visibility graphs were analyzed using Pajek, software for graph analysis developed by Baragelj and Mrvar at the Department for Theoretical Computer Science and the Faculty of Social Sciences at the University of Ljubljana, Slovenia and available over the web (http://vlado.fmf.uni-lj.si/pub/networks/pajek). Of the various measures computed by Pajek, the most useful for our research was the simplest, namely degree. The degree of a node measures the number of arcs incident upon it. As we deal with directed graphs, a distinction is drawn between degree "in to" and degree "out from" a node. In order to be consistent with the terminology of previous studies, we will use the term "Connectivity" rather than degree. We will show that "connectivity in to" a node is a good predictor of behaviors. It is important that our measure of connectivity is not confused with similar measures as applied to non-directed graphs. Figure 3c shows the full cross-visibility directed graph overlaid upon a sample layout.

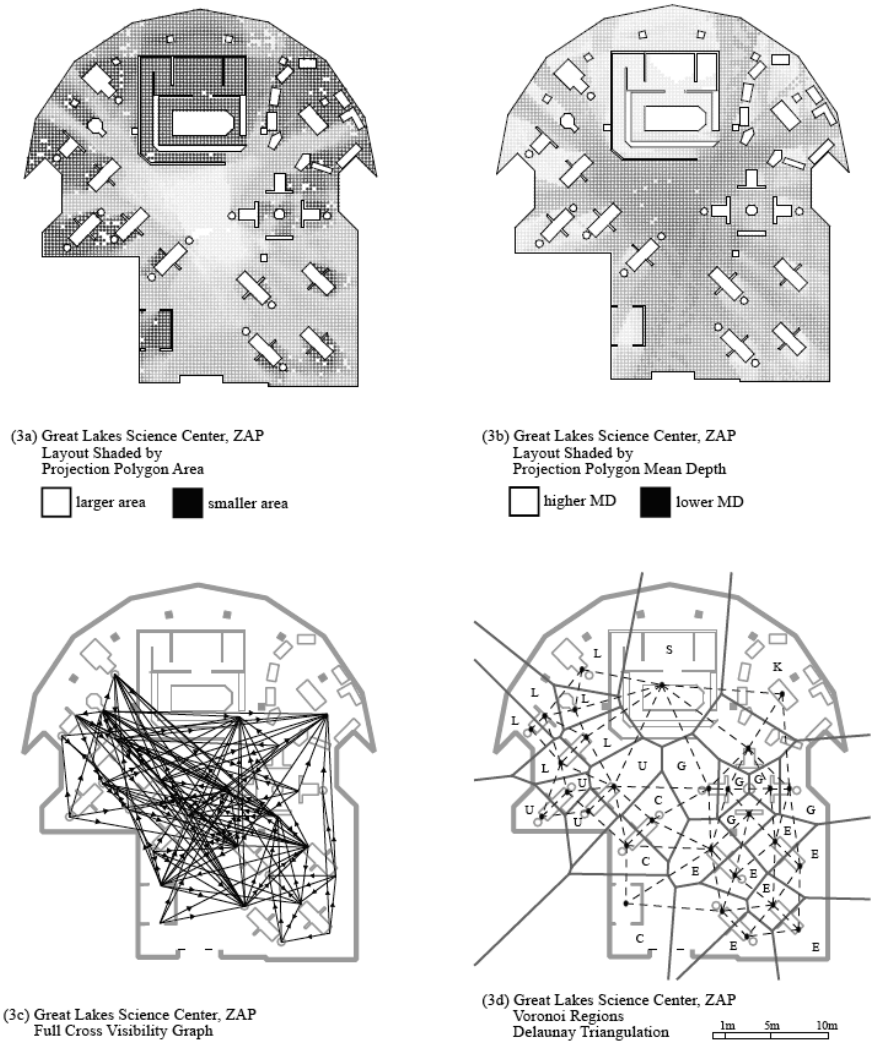

Fig. 3. Visual representations of the main spatial descriptors for one of the settings.

Table 2 presents a simple quantitative profile of the four settings. It shows that each exhibit element can be directly reached from at least 8% and up to 14% of the total exhibition area, depending on the setting. Also, no more than three direction changes are ever necessary to go from any point within an exhibition to another. Regarding cross-visibility, the table shows that between 1/3 and 2/3 of all other exhibit elements are at least partially visible from each exhibit element. These numbers confirm the permissive and open character of these layouts regarding the potential exploration paths taken by visitors.

At the simplest level, the spatial structure of layouts arises as objects and boundaries are placed in space. Objects and boundaries work as obstructions that limit

potential visibility and/or movement. The greater the limitations upon movement, the more movement patterns are distributed according to the layout. The overall question asked in this section is quite straight forward: how do patterns of accessibility and visibility affect the pattern of exploration, visual contact and active engagement with exhibition contents?

Table 2. Quantitative profile of the four exhibition settings

	ZAP! Surgery Great Lakes Sci. Center	ZAP! Surgery Carnegie Sci. Center	Robotics Great Lakes Sci. Center	Robotics San Jose Tech Mus.
Total Exhibition Area (square meters)	724	707	724	498
# of individual exhibits (excludes children's area)	27	27	35	25
Average full individual exhibit cross-visibility from other individual exhibits (% of all individual exhibits)	21.8%	12.5%	19.4%	36.6%
Average partial individual exhibit cross-visibility from other individual exhibits (% of all individual exhibits)	41.8%	28.9%	51.7%	59.9%
Avg. Projection Polygon Area (from which an individual exhibit can be reached directly)/(Square meters)	83.24	54.81	102.93	58.72
Avg. Projection Polygon Area As proportion of total Area	11.5%	7.8%	14.2%	11.8%
Avg. Projection Polygon Mean Depth (direction changes needed to reach from any position to any other)	2.472	2.280	1.958	2.067

The relationship between spatial and behavioral variables was studied based on linear correlation coefficients. We examined correlations between the Area and Mean Depth of projection polygons corresponding to individual exhibits and the four measures of behavioral attraction presented above, namely "1St Contact", "Repeat Contacts", "1st Engagement", "Repeat Engagements". We also explored these relationships for three samples: first, all people observed, that is about hundred people per setting; second, the 25% of the people that spent more time in the exhibitions; third, the 25% of the people that stayed less time. (The specific results of these analyses and statistical details are reported in a previously published paper, see Peponis et al., 2004. For the current paper, results will be presented in summary form.)

Our analyses indicated that contact counts were significantly and powerfully correlated with polygon Area. This finding, perhaps not surprisingly, suggests that exhibit elements with larger areas of direct access were associated with greater numbers of visitor contacts. Correlations with Mean Depth were less consistent,

showing only a trend that exhibit elements at greater depth were associated with fewer contacts.

When we looked at engagement with an exhibit element instead of simply contact with it, we find very different results. Engagement counts were not consistently correlated with polygon properties. Neither a larger area of direct access (polygon area) nor more direct access (fewer changes of direction or mean depth) was associated with higher levels of visitor engagement.

These results suggest that the direct accessibility of exhibit elements has a powerful effect on the manner in which the exhibitions were explored, as indexed by the distribution of contacts. Interestingly, layout seemed to work similarly for people that stayed longer and people that stayed shorter lengths of time. We might infer that layout structures the search pattern based on its most simple local properties. However, this pattern of accessibility does not similarly predict visitors' choices to engage particular exhibit elements. Further analyses showed differing effects of spatial layout on engagement patterns.

Our analysis examined linear correlations between the Full and Partial measures of individual exhibit cross visibility. Although we found correlations between our measures of visibility and visitor contacts, our results suggest that cross visibility does not affect contacts as consistently as accessibility. Cross visibility, however, had quite powerful effects upon the pattern of engagement. We concluded that exhibit elements that were visible from other elements would attract more active engagement. Furthermore, we suggest an informal pattern of spatial learning by comparing the correlations associated with visitors that stayed longer or shorter lengths of time. There was good evidence that as people stayed longer, the visibility of exhibit elements from other elements had a more detectible effect upon decisions to engage those exhibit elements. The term "informal spatial learning", as used here, refers precisely to this gradual adjustment of behavior to spatial variables; spatial variables produce more powerful affects on visitor behavior as the overall exploration time increases.

To further our exploration, we examined the effects of layout upon the sequencing of contacts or engagements. We checked to see if there were differences in the average Area and the average Mean Depth of the projection polygons for the first half of a visitor's path as compared to the latter half. We found no such tendency. Indeed, individual visit paths appeared to oscillate between more and less accessible positions, positions associated with higher and lower Mean Depth, throughout their length. Thus, the patterns of accessibility and directional distance had no strong effect upon the sequencing of exploration and individual exhibit engagement.

In an effort to extend our understanding of the visual and perceptual properties of exhibition design we examined the effect of arrangement of exhibits according to conceptual organizing themes (see theme labels in figure 3(d)). In these open plan exhibition areas, where movement and visual attention are not controlled, conceptual grouping is expressed either through inscriptions (explanatory texts affixed to the exhibits) or through design features such as color or, indeed, through the spatial arrangement of exhibits into clusters or patterns of proximity. To understand the effects of theming on visitor movement, we identified typical visitor paths and examined the extent to which exhibit elements carrying the same thematic labels appeared sequentially within the overall visit sequence or were dispersed along that

path. Plans were also analyzed to determine to what extent individual exhibits with the same thematic label were spatially adjacent (encouraging sequential viewing) or dispersed. (For this analysis, a grouping index was developed for each layout based on Voronoi diagrams and Delaunay triangulation, see example provided in figure 3(d).)

The plans were analyzed to determine the number of Delaunay arcs corresponding to adjacencies between individual exhibits belonging to the same thematic label and the number of Delaunay arcs corresponding to adjacencies between individual exhibits belonging to different thematic labels. Two grouping indexes were obtained based on the foregoing representations. The Individual Exhibit-Sensitive Grouping Index, $GE_{(l)}$ for easy reference, is the average of the ratio "internal"/"external" Delaunay arcs, computed for each set of individual exhibits corresponding to the same label "l". The Label-Sensitive Grouping Index, $GL_{(l)}$ for easy reference, is the ratio "sum of internal"/"sum of external" Delaunay arcs considering all the individual exhibits belonging to the same label. Thus, $GE_{(l)}$ is an average of ratios, while $GL_{(l)}$ is a ratio of sums. (For further details on these analyses see the previously published paper, Peponis et al., 2004.)

The effect of the spatial grouping of labels upon the categorization of visitors' paths was analyzed by computing linear correlations between the Categorization Indices and each of the two Grouping Indices for each label. These correlations are presented in Table 3. Given that the number of thematic labels in the exhibitions under study is limited, data were analyzed not only by setting but also at different levels of aggregation, in order to allow for statistical significance in the results. When all settings are considered as a single set, we found a strong tendency for visitors' paths to be more theme-oriented when exhibit elements within thematic groupings were more clustered. The correlations are even stronger for engagements than for contacts.

This requires some explanation. It is true that contacts must, to some extent, be sequenced according to the constraints of the layout. As a visitor moves through an exhibition, she may not engage adjoining exhibit elements; however, her path will pass these exhibits (what we consider to be a 'contact'). This is why the analysis of engagements is more interesting than the analysis of contacts. Spatial groupings of themes would obviously impact contacts but less obviously engagements. *Engaging* an exhibit is different; engagement reflects a conscious decision not dependent upon adjacencies. In fact we found that the spatial grouping of themes affects engagements more powerfully than contacts, suggesting that behaviors reflect the cognitive registration of thematic labels. When we looked at these effects by setting, we found stronger correlations for the Zap exhibition than for the Robotics exhibition. In the Zap exhibition the thematic labels were more clearly grouped spatially, but also more clearly expressed visually through the use of color. (We can say with some certainty that spatial groupings of exhibition elements within themes results in visitor engagement sequences that also remain within themes; however, because of our limited sample (two exhibitions in two settings) we can only speculate regarding the effects of making the themes more visually prominent; furthermore we acknowledge that we do not know if the themes are in fact cognitively registered.)

Table 3. Correlations between the grouping of themes in the layout and the categorization of path strings representing contacts and engagements (significance shown in parentheses).

		Contacts	Engagements
All strings	GE	.551	.605
		(.0024)	(.0006)
	GL	.67	.693
		(.0001)	(.0001)
All ZAP! strings	GE	.471	.616
		(.0892)	(.0190)
	GL	.638	.713
		(.0141)	(.0042)
All robotics strings	GE	.721	.408
		(.0036)	(.1480)
	GL	.582	.391
		(.0291)	(.1670)
ZAP! Great Lakes Science Center strings	GE	.221	.644
		(.6341)	(.1184)
	GL	.462	.707
		(.2964)	(.0758)
ZAP! Carnegie Science Center strings	GE	.715	.586
		(.0710)	(.1665)
	GL	.798	.725
		(.0316)	(.0654)
Robotics Great Lakes Science Center strings	GE	.691	.338
		(.0855)	(.4579)
	GL	.621	.416
		(.1366)	(.3528)
Robotics San Jose Tech Museum strings	GE	.887	.515
		(.0078)	(.2371)
	GL	.723	.470
		(.0663)	(.2874)

We can summarize our findings as follows: Within open plan exhibition areas, visitors will contact more accessible exhibit elements over the course of their visit. Where visitors stop and engage exhibit elements will be influenced by spatial characteristics of visibility. Visitors tend to engage exhibit elements that are more visibly evident. As visitors spend longer in the exhibition, this effect becomes more evident.

We propose a set of principles that suggest how spatial layout affects visitor behavior:

1) The most generic, but perhaps less interesting, principle is that direct accessibility affects the exploration pattern of visitors; the more accessible an exhibit element is from all other exhibit elements, the more likely it is to be visited.

2) The less generic, but perhaps more interesting, principle is that as visitors stay longer they become more aware of those exhibit elements that are more visible from other exhibit elements and decide to engage them.

3) Although overall a visitor will contact more accessible exhibit elements and engage more visible ones, typical visitor movement paths will include more and less accessible exhibit elements as well as those that require more and those that require fewer changes of direction (directional distance) dispersed throughout their visit. This suggests that although visit paths vary by individual, as one would expect under these open plan conditions of high accessibility and high visibility, the viewing patterns across the population of visitors are more evenly distributed.

This process of relatively unstructured and locally driven exploration can be constrained by making the thematic organization of exhibit elements more apparent. If themes are not made perceptually evident, visitor search patterns tend to intersect thematic groupings randomly. However, if the curatorial intent is to channel movement more systematically according to thematic groupings, this can be achieved if themes are made perceptually evident. Thus, thematically linked individual exhibit elements could be treated as contributing to a more constrained and structured exhibition narrative. From an analytical point of view, theming can be conceptualized as the addition of relationships between objects over and above those involved with the patterns of accessibility and visibility.

To add a fourth principle:

4) Visitors tend to engage exhibit elements within thematic groupings, and the more visually coordinated and spatially grouped the elements, the stronger this tendency.

These principles suggest a model of visitor behavior that involves an open-ended search process that is subtly structured by spatial variables. Based on this model, a rather obvious prescription for exhibition design is that exhibit elements should provide relatively autonomous and self contained information at each position, and that the more critical exhibit elements should be positioned in more accessible places and made more visible from other exhibit elements in order to increase the probabilities that they will be contacted and engaged. Furthermore as the properties of layout that affect the probability of contacts or engagements vary independently of particular path sequences, the model also suggests that good exhibit element design should be independent of sequence and that the 'message' drawn from successive engagements be flexible. This is a far more demanding requirement but one naturally associated with open and permissive open plans and one clearly adopted by the designers of the exhibitions under study. Finally, designers can influence the pattern of visitor exploration through the spatial grouping and visual coordination of exhibit elements according to themes.

This link to cognitive function is worthy of further consideration. In an exploratory study, Allen (2006) found that the placement of partitions around related exhibits improved visitor recognition of common themes. For Allen's study, a small cluster of six exhibit elements was enclosed using fabric partitions. The enclosure surrounding the elements was essentially circular in shape with a large space between partitions for entry and exit, a layout described as 'a pair of parentheses' around the elements. The resulting arrangement was quite open, rather than a true enclosure. Examining the behavior of a sample of 400 visitors (half under 'no walls' condition and half under the 'walls' condition), the study assessed the cluster's attracting power (stops), number of elements visited, total holding time, and thematic coherence (understanding of the underlying theme; assessed through post-visit interviews from

160 visitors). Results indicated that the number of visitors who stopped within the cluster was significantly lower under the 'walls' condition than without walls. Of those who stopped, the holding time with walls was longer than without walls attributable to both stops at more of the elements within the cluster as well as longer engagement time with the most popular of the exhibit elements. Furthermore, significantly more of the visitors to the 'walls' condition could correctly identify the theme of the cluster.

Enclosure appears to encourage longer visit time, visiting greater numbers of elements and comprehension of common themes. However, the use of partitions constricts views, and, as we have shown, affects visitation. Although we do not have definitive results at this stage of our research, our study suggests that, through the use of spatial grouping and visual coordination of exhibit elements according to themes, a more structured exhibition narrative may be achieved without the constraints of physical containment and prescription.

In summary, it is clear that in museums, visual fields and spatial structures modulate patterns of movement and associated modes of seeing and understanding. The configuration of space structures patterns of exploration whether on the global scale of movement through the museum building or on the local scale of movement through an open plan exhibition space. Configuration also tends to structure the occupation of space through the modulation of visibility patterns, whether it is the visibility of other visitors that affects where visitors tend to stop as they explore the museum building, or the visibility of exhibition elements that affects where visitors stop in open plan exhibition spaces.

5 Concluding Comments

This paper reviews research that, taken as a whole, augments the manner in which spatial organization and its effects are understood in museum studies. Space is of course important in museum design in a number of ways ranging from the availability of areas and surfaces to display exhibits, to the creation of a particular ambience; from the construction of particular perspectives, to the creation of appropriate visual comparisons. Space is also important as a framework of orientation: when visitors know where they are in a building, they can better understand their location within the narrative presented to them by the exhibition curators. Space syntax allows us greater precision than was previously available in analyzing space as a relational structure arising from the arrangement of objects and boundaries, whether at the scale of the building as a whole, or at the scale of the individual exhibition or exhibition room. This seems particularly appropriate to museum studies. In the context of a museum, the display of the individual object can rarely be dissociated from the manner in which the individual object is related to the collection. Museum experience cannot be reduced to an accumulation of individual viewing impressions, but has to be understood as a configurational pattern encompassing many different displays as well as many different points of view, at least some of which are comparative.

The emphasis of the research reported here is on the behavioral functions and the behavioral consequences of space: we have discussed exploration and movement

paths, patterns of co-presence and co-awareness arising within the visual field, patterns of contact and exposure with displays and patterns of engagement. However, by demonstrating that these behavioral patterns are systematically correlated to spatial variables, we have also demonstrated that they can themselves be understood as spatial morphologies. In this manner, we seek to enrich the way in which visitor behavior is understood in museum studies. From a methodological point of view, learning to describe behavior as a spatial morphology is as important as learning to describe the arrangement of museum space itself.

While we have not directly engaged issues of visitor understanding and learning other than through its overt and evident behavioral dimensions, it is tempting to conclude with some comments on the prospects of spatial analysis in this regard. Should the cognitive effects of the spatial structure of museums be treated in terms of narrative? In so far as exhibition design can create spatial sequences and visual frames for viewing it would appear that space can function as a support for narration in the sense of a purposefully established sequential pattern of presentation analogous to the sequential pattern of language. This is certainly the aim of several exhibitions, especially exhibitions with historical subject matter or exhibitions presenting complex scientific discoveries. However, the research reported here suggests that the cognitive functions of museum space are not always a matter of supporting narrative presentations. Indeed, thinking of museum space in terms of narrative, in any strict sense of the word, may miss the important issues. Instead, it may be more appropriate to think of space as an independent medium for constructing meaning, that is, as an independent medium for suggesting relationships. The most generic cognitive function of museum space is that suggestion of particular ways of seeing, linked to particular ways of understanding relationships not only through seeing but also through movement. In other words, the spatial structure of a museum, or an exhibition, is its own message in addition to possible contributions to conveying linguistically stated messages. Thus, for example, space does not cease to function cognitively when possible viewing sequences are multiple and to some extent unanticipated and when viewing engagements are selective and only statistically predictable. In future work, the morphological structure described here, whether the spatial morphologies of exhibitions or the spatial morphologies of behaviors, are likely to be correlated to cognitive morphologies that cannot always be reduced to strict narrative sequencing. However dimly research reported here may point to future research on the cognitive consequences of museum and exhibition design, the need to look at space as a medium in its own right rather than as a narrative support is perhaps already clear.

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Configuration and Neighbourhood: Is Place Measurable?

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Abstract. This paper seeks to determine if place or, more specifically, neighborhood is a purely social cultural construct or a reflection of the society embedded in the physical environment. A new method of spatial analysis based on space syntax methods called point intelligibility mapping is introduced. Using an example from Lynchs The Image and The City, the method is found to successfully extract the neighborhood boundaries from a syntactical topological map of Boston.

1 Introduction

Currently, the field of architectural inquiry termed space syntax (deals with a range of basic questions, including if architecture has any measurable social outcome. One of the most important and consistent findings is that the configuration of the network of definable spaces strongly influences the pedestrian movement economy in building an urban settlement. This analysis of flow through place has a wide rage of outcomes, including identifying regions or spaces of high encounter, and hence the potential for greater social interaction. Further study of flow can also be used to identify and to understand the operation of flow-dependant buildings such as retail.

One might argue that the weakness of space syntax is its inability to formalize and exploit some of the common currency of social, geographical, and architectural debate, such as place or neighborhood. While there have been some very good investigations into the definion of place (Couclelis ,1992) In this paper, we will restrict the definition of place to refer to a geographically restricted set of buildings, typically including domestic stock, which constitutes a social space or a setting for social interactions or more commonly a neighborhood neighborhood. Prior to Hillier, one of the principle theories in architecture was Lynchs (Lynch,1965,Lynch 1960) concept of legibility and imageability. Lynch states:

Clarity of structure and vividness of identity are [the] first steps to the development of strong symbols. By appearing as a remarkable and well-knit place, the city could provide a ground for the clustering and organization of these meanings and associations(Lynch 1960).

Lynch identifies the necessary conditions for the evolution of place from the urban environment. Place or neighborhood is implicitly present in space syntax theory but not as a descriptive object (R. C. Dalton Bafna, 2003). In Space is the Machine, Hillier (Hillier,1996); introduces the concept of intelligibility, a network or topological graph measure of the whole structure of a settlement. Hillier indicates that the objective measure of intelligibility can be used to measure the degree to which an area or part thereof might be said to be navigable. Difficult to navigate locations, such as dysfunction housing estates/housing projects, can typically show a low intelligibility factor. In this manner, Hillier demonstrates that space syntax lies deeply within the field of structural positivism.

However, many in the field implicitly believe that a neighborhood is an imposed construct. To measure the intelligibility of a neighborhood, one first must select all of the lines in the defined geographic region. This implies that the limits of the neighborhood are known (at least roughly) prior to their selection, which suggests that neighborhood or place is an implicitly agreed upon concept. For example, the neighborhood known as Dartmouth park a district in the London Borough of Camden, England could be removed from every map and declared by government dictate to cease existence (such as happened to the country of Rutland in 1974). As a social construct, the named entity only exists within the realm of the conceptual, and concepts can be changed. Would the feeling of being in a place then change? Equally, arbitrary cross sections through London could create a number of neighborhoods but would this create a sense of place? As social constructs, it should be possible to create new places by social agreement. In this case, their meaning lies purely in the utility by which people refer to arbitrary sub-zones of the city and the associations that these locations have with their occupants. In this case, Relphs (**?**) concept of placelessness, or the lack of feeling of a neighborhood, is entirely due to sociological aspects; this dooms the attempts of New Urbanists (Katz, 1994) to try to design in place or neighborhood. Further it could be said that both Relph (1976,page 29) and Langer (Langer, 1953) appear do reject the notion of the involvement of location and therefore environmental configuration in the formation of place. For the purposes of exposition, this place as purely determined by cultural phenomena will be referred to as cultural determinism; this deliberately parallels the concept of purely environmental causes of place that is labeled environmental determinism.

The alterative to this purely cultural hypothesis is that there is some aspect of the local physical environment that facilitates the evolution of a neighborhood. Clearly, it is always possible for localities to be designated as official places for administrative convenience, but these localities may not give the feeling of being a single neighborhood or place; in other words, they may be placeless. In this alternative hypothesis, neighborhoods and the feeling of place are rooted to some strong extent in the physical fabric of the local physical environment. Neighborhood is an interaction between a specific locality and the people living within that locality: people give rise to place, which leads them to create associations

with that place that ultimately create meaning; this facilitates the naming of the object (for example, Dartmouth Park). If the null cultural determinism hypothesis is true, then it should be impossible to extract any manifestation of neighborhood from the environment except for that which was put as a reflection of the culture of the neighborhood. For example, signs labeled historic district and garden district are not physical manifestations generating neighborhood but expressions of the existing culture of the district. If most neighborhoods possessed a park or landmark prior to the formation of the cultural aspect of neighborhood, then this might indicate the inadmissibility of cultural determinism.

2 Method

As mentioned, Hillier has already suggested a process that can assess an attribute neighborhood: its intelligibility. In this paper, we introduce two new forms of syntactical mapping called point intelligibility mapping and point synergy mapping. To understand this, we must return to the core of the syntactical mapping method. In this case, an urban system is disaggregated into a number of separate spaces. A space in the space syntax method is the basic building block of urban and building systems combined. A component space is what we inhabit at home or at the office. The city is the sum of all component spaces and is continuous; we can move from location to location by passing through a number of spaces. A space in the syntactical sense is a prescribed component of all spaces. Although there are a number of ways of describing space, we will focus almost exclusively on the axial line, which is a convenient object to describe an urban system.

Space in the Hillierian sense should then be different from that in the spatial science sense (Cresswell, 2004) and somewhat similar to that of place in the terms of humanistic geography as suggested by Tuan (Tuan, 1977) and Seamon (Buttimer Seamon, 1980). Like place, the meaning of syntactical space comes from the flow of occupation and traversal and the potential for human encounter that it affords. A space in space syntax also shares similarities with location. It is externally definable and can be used in mathematical operations. Unlike location, a space can contain a number of locations, and some locations can occupy more than one space. For space syntax, space is the unit of understanding the social dimension to human settlements. Figure 6 shows an axial map of central Boston showing all the identifiable axial spaces in the settlement.

From the space syntax point of view, the objective measurement of the configuration of space is fundamental to understanding the social logic of a settlement. Given that a settlement can be divided into a number of spaces, each space interconnects with the immediate spaces around it; ultimately, through intermediate spaces, it is possible to reach all spaces in a settlement. A measure of the configuration of a settlement can be produced by selecting a starting space and then grouping all of the spaces that are directly connected into set S1. All of

the spaces that are connected to S1 but are not a member can be grouped into set S2, and so on. By measuring the size of these sets, it is possible to measure the degree of centrality (integration in syntactical terms) of the original starting space or spaces. Much of the predictive power of space syntax comes from the strong correlation between pedestrian movement observed in that space and the configurational measures (typically the integration factor) of the spatial network for that space.

3 Point Intelligibility mapping

Hillier (Hillier, 1996) defines intelligibility as the correlation between the degree or connectivity of a space and its integration factor. This value potentially ranges from -1 to 1 or more typically from 0 to 1. In this case, 1.0 implies a completely reliable (substitutable) prediction of the global integration pattern from the local connectivity 0.0, the lack of any relation or a random relation. For a neighborhood, Hillier shows that for a subset of all lines is possible to find the intelligibility factor for any subset. This method can be used to select a sub-area or neighborhood from a larger axial map and to find its intelligibility.

Point intelligibility mapping begins with the definition of a single axial line space or node in the graph. The subset of all the nodes in the graph are chosen by selecting all of those that are connected to the starting line/point/node along with those that are connected by, at most, two other lines/points/nodes to the starting point. Thus, any point in the subset is at most three steps from the starting point. This process is analogous to the concept of radius used in space syntax. It creates the topological neighborhood of the axial lines rather than a distance-based metric. This neighborhood can then have the correlation between the global pattern of integration and the local value of degree or connectivity computed and assigned as an attribute to the line. That is, the point intelligibility for a line is the local correlation between integration and connectivity for the locality centered on that line.

While the exact size and contents of a set may change slightly, it is clear that if a group of lines share a great deal of similar lines within the group, then they are likely to share the same local set of values and hence a similar point intelligibility map.

Figure 1 shows the plot of the values along the continuum from thin/grey = 0.14 and thick/black =-0.8. The first observation is the larger circle that roughly corresponds to the area called Somers Town, discussed as a neighborhood in the social logic of space. When investigating the map, the large negative values (one identified by small circle) appear to be caused by chance correlations computed from small number (4) nodes in the radius 3 group. This skews the distribution making it hard to ignore the natural small variations within an area. We could solve this problem by excluding all of the lines with small unrepresentative local sets or by using the concept of point intelligibility by vicinity.

Fig. 1. Plot of aixal point intelligibility for Kingscross area - problem line in dotted circle. Thick lines indicate low point intelligibility values, thin light lines for high values

Introducing the concept of vicinity, Dalton (S. N. Dalton, 2005) proposes to solve the problem of mathematics of angular relativisation by using a fixed size group. This is based on the concept that only the N closest (by radius) items are used. The typical objection to vicinity is that the number of items encountered is unlikely to include all of the nodes from a typical radius; the choice of remaining nodes is arbitrary. First, it should be noted that all of the nodes with a step depth less than radius R will be included. Secondly, for the case of described by Dalton, it should be pointed out that the choice will be a subset where the value is the same; that is, we need to arbitrarily select 10 nodes from 18 where all of the nodes have a value of 3. In the case of relativisation, any permutation of 10 nodes at depth 3 will contribute 3*10 = 30 to the total depth, regardless of the permutation chosen. As such, Dalton is able to neatly ignore the problem of ordering.

In this paper, we will use the concept of vicinity to provide a fixed size set around the space, axial line, or node of interest. By using a fixed local set we hope to elimiate the problem of stray extreme correlations due to small sample sizes. To break the arbitrary selection problem described above an additional method is used., Every axial line or node in the graph has 3 values: depth from the starting node in question (d), integration value (I), and connectivity/degree (k). Arbitrary permutation can compute different values for integration (I), and connectivity/degree(k) are likely to be different for a given value of depth D; this can be remedied by choosing a representative same of nodes for the same

depth. If a subset of size S of N nodes at depth D is used, then the nodes at depth D are ordered by Integration I. For example, if 2S = N, then every other node is selected. If 3S = N, then every third node from the set is chosen. This process can be generalized for any set size of S and N to give a fixed, non-arbitrary, and representative sample. Thus, it is possible to find a non-arbitrary, repeatable, and representative subset, hence a vicinity set of lines for a given starting node. With this method, we can repeat the radius-based method described above but remove the unrepresentative set. This creates a vicinity limited point intelligibility map.

Fig. 2. Plot of axial point intelligibility map for Kingscross area, Somers town neighbourhood in dotted circle

We can now see that the small scale variation of Figure 2 is reduced and that the colors (values of intelligibility from the vicinity of line) are more consistent. Again Low point intelligibility lines are thin/ligte gray and the high intelligibility ones are thick/back. Figure 3 is marked with a circle to indicate an area of near-constant point intelligibility. Note that there are other similar areas of color to the west of Summers Town. To the north of Summers Town, we can see that Camden Town has a distinctively different value (thick/dark gray representing a value of approximately 0.5). Before discussing this result, a second measure needs to be introduced.

4 Point synergy mapping

Space syntax seeks to understand the local scale in the global context. For small maps, one can reasonably expect to walk from any origin to any destination on foot. For larger towns and cities, it is likely that many trips are beyond the reasonable walking range. The local view of the entire city becomes an unrepresentative measure of the graph. Hillier and Hanson (Hillier & Hanson, 1984)introduce in the social logic of space: radius, or the region within a number of steps on the graph or changes of direction on the axial map. This creates a window or smaller sub-graph of the larger map. Numerous studies have demonstrated that pedestrian movement likely correlates most strongly with the values of radius 3 on larger maps. For this, Hillier and Hanson needed to introduce a relativisation process that permits graphs of different sizes to be compared. In Space is the Machine, Hillier (1984) defines synergy as the correlation between the value of radius 3 integration and radius infinity correlation. He demonstrates that in known locations, such as the city of London in London, there is a strong local correlation that typically has a stronger slope than that of the city in general.

Point synergy by vicinity works similarly to point intelligibility by vicinity. For each line, the most local V lines to the starting line are chosen. The local correlation between the values of integration and integration radius 3 are computed. This value (between -1 and 1) is then assigned back to the line for later visualization. The process is repeated for another starting line until all lines have a point synergy value computed.

Figure 3 illustrates that the point synergy map gives a value of near constant point synergy factor over the extent of the neighborhood and a sharp discontinuity of value when entering the area to the north known as Camden Town. Sommers town is again circled.

From this example, the method of point intelligibly mapping and point synergy mapping by vicinity appear to have identified the extent of a known neighborhood purely from spatial configuration of the urban London environment. It might be argued that the area known as Summers Town was chosen from the social logic of space by the authors and does not reflect the true extent of what local inhabitants think of as their neighborhood. To counter that concept, we will move on to a case study based on the work of Lynch.

In The Image of the City, Lynch (Lynch, 1960) examines the neighborhood known as Beacon Hill in Boston, Massachusetts, USA. Lynch interviews local inhabitants to assess the extent rather than the location of Beacon Hill. Long-term residents or those employed in an area were asked for images which invoked their own images of their physical environment. The interview included requests for descriptions, locations, and sketches, and the performance of imaginary trips(Lynch, 1960). pg 17). Part of this interview process included trying to identify what streets defined the boundaries. During this process, he elucidates

Fig. 3. Plot of point synergy map for Kingscross area, vicinity factor or 90, Synergy is radius 3 radius infinity, Sommers town marked by dotted line.

that the extent of Beacon Hill is rather well- defined (something which he goes on to demonstrate is not always the case with all areas). Furthermore, the locals reveal there are two primary sub-areas known as front-side and back-side, these sub-areas have an identity that can be traced back to antebellum times and traced forward to today. One current inhabitant of Boston described them as north-side and south-side. The radius 3 integration map created by N. Radford (N. Raford, 2004; N Raford & Hillier, 2005) is presented in figure 4.

We can see from this map that the Beacon Hill area does appear to have a wide variety of movement types within itself. The site has both streets with high integration, expected to be high pedestrian movement and likely to be sites for retail, and a full spectrum through to low volume (thick dark) streets, typical of private residences and parks.

Figure 5 defines front-side and back-side as nearly constant values of point intelligibility across them but different values from each other. Notice also that the area Lynch refers to as the lower hill maintains a similar but slightly different level of point intelligibility across its extent.

Clearly, what has happened in both the case of point intelligibility and point synergy mapping is that the values of near-constant point intelligibly are broadly similar across their extents and to their boundaries. The regions discovered by Lynch from mapping the subjective notions of a community show strong corre-

Fig. 4. Axial Map of Boston, USA with Beacon Hill identified within dotted region, thicker darker lines indicate higher integration.

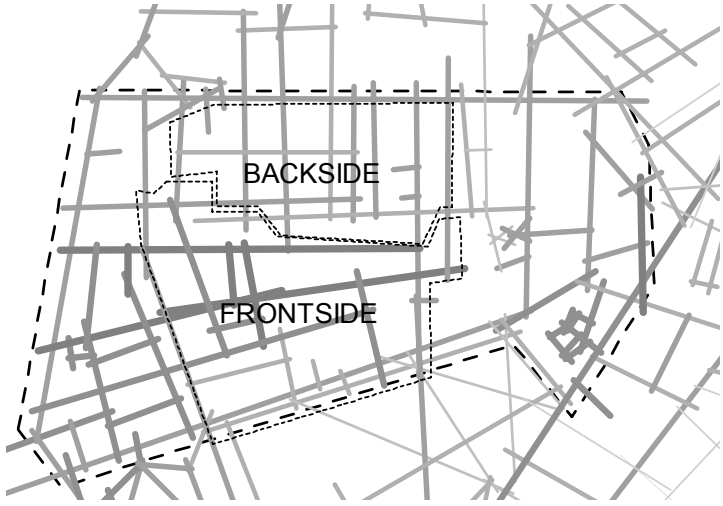

Fig. 5. Point synergy map distribution of Boston with Lynch neighborhoods frontside and backside circled in dotted regions.

lations with the objective measures of point intelligibly arising from the configuration of the open space. Created by rule from the geographic map of the city, the axial map is a measured representation of the purely spatial external world without prior knowledge of the neighborhood of front-side or back-side. The only information here was the configuration of the space for pedestrian movement. This local spatial configuration largely extends back to the original construction of the region in the early (pre-Independence) development of Boston itself. If the concept of that neighborhood is a purely social or aspatial construct (the cultural deterministic view), it would be impossible for the region and bounds of that neighborhood to be extractable via any technique. In this case, we have demonstrated that the conceptual neighborhood is consistent with the objective spatial/configurational measure. What has not been demonstrated is if the area known as Beacon Hill can also be found.

Fig. 6. Axial map of Boston area showing the point synergy factor for vicinity of 180 and synergy of radius 4 against radius infinity. Beacon Hill area within dotted area

Figure 5 shows a point synergy map showing the local point correlation between radius 3 and radius infinity for a local area defined by a vicinity of 90. The value of radius 3 is a value typical of pedestrian movement in general. The value of vicinity of 90 was chosen from research to establish the best vicinity that produced movement values to correspond well with radius 3 integration.

Taking the vicinity factor, as this value grows, it will eventually reach the number of lines in the city. At its largest, the whole city will emerge with one point synergy value for the city. This value may well be different from that of other cities and describes the intelligibly of the named object, in this case called Boston. Cities have more than local neighborhoods, which have strong meaning to the individual but not necessarily to the global population as a whole. Between the level of the local neighborhood and the city, there can be a number of levels of hierarchy. If we alter both the vicinity and the synergy radius between the local and the global, new hierarchal areas may well emerge.

While there are some interruptions such as Charles St (see Figure 6, large thick line in the centre of the indicated area) the point synergy map with a vicinity of 180 and a synergy radius of 4 shows a great deal more internal similarities than differences and also has more differentiation with the surrounding areas. Again, if Beacon hill were a purely social concept, it would be impossible to extract any bounds from the purely configurational analysis performed.

5 Conclusions

Given the preliminary data presented, it appears consistent that some aspects of the neighborhood are embedded in the configuration of spaces that made up the urban environment. That is, the area that can be extracted from the phenomenological experience of neighborhood (the place in which we might exist and of which we feel a part) corresponds to that defined by an objective discursive measure of space. Does this imply that there is a topological environmental determinism present? The evidence does not appear to support this: a view of the map of London shows that while named locations are generally present in the point intelligibility map, there are also a number of areas that have no name. In theory, these are the extents of potentially named places that might one day be given a name depending upon the social process. Not all of the spaces in an urban system can be neatly defined as potential spaces. Some regions have little local consistency, so there is little affordance offered for the formation of place; that is, they have location but not spatial consistency. If these locations are defined culturally as places (e.g. Disney Land, perhaps Celebration), then perhaps an inhabitant or visitor might experience the deviation between subjective experience of the configuration of space and the cultural declaration of space that Relph (Relph, 1976) defines as placelessness.

The theory that might explain the measurable existence of place may well be that of facilitation and affordance rather than that of causality. The measure of point intelligibility mapping and point synergy mapping demonstrate the natural boundaries to locality caused by the configuration of spaces. These weak invisible natural boundaries may influence our daily perception of what is here and what is somewhere else. Once an area is defined by weak boundaries, we begin to see a place co-evolving, defined by Lukerman(Lukermann, 1961) as integrations

of nature and culture through the movement of goods and people. The use of point intelligibility mapping and point synergy mapping also appears to help elucidate our understanding of the urban neighborhood. If though further testing the hypothesis that the configurationally foundations of a neighborhood can be objectively measured then it may be possible to investigate the evolution of place and neighborhood in a rigorous way.

Certainly, the strong cultural determinism hypothesis appears to have been undermined by the evidence presented. This should been seen as a positive outcome for architects and urban planners it gives added impetus to the importance of design outcomes on the evolution of neighborhoods.

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From Isovists via Mental Representations to Behaviour: First Steps Toward Closing the Causal Chain

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Abstract. This study addresses the interrelations between human wayfinding performance, the mental representation of routes, and the geometrical layout of path intersections. The virtual reality based empirical experiment consisted of a route learning and reproduction task and two choice reaction tasks measuring the acquired knowledge of route decision points. In order to relate the recorded behavioural data to the geometry of the environment, a specific adaptation of isovist-based spatial analysis was developed that accounts for directional bias in human spatial perception and representation. Taken together, the applied analyses provided conclusive evidence for correspondences between geometrical properties of environments as captured by isovists and their mental representation.

Keywords: Isovist – geometry – wayfinding – spatial cognition – landmark knowledge – route knowledge – virtual reality

1 Introduction

Although original space syntax measures mainly addressed relations between spatial structures and society, recently several researchers have applied these descriptions to quantify relations between environmental structures and individual behavioural responses [e.g., 5, 14, 35]. While the obvious success of these studies has backed this extension of the original scope of the analyses, conclusive explanations or insights into the mechanisms underlying these statistically observable patterns have not yet been provided. Unlike mindless agents, human beings normally do not solely respond to a given spatial stimulus, their navigation behaviour rather results from mental planning processes and the monitoring of goals, processes which are continuously updated according to the current perceptual context. Therefore, in order to proceed from the mere description of correlations between environmental structures and averaged spatial behaviour to qualified predictions and explanatory models, in other words to identify the causal processes which start from environmental structures and lead to behaviour, it seems necessary to determine the perceptual and mental

processes underlying these behavioural patterns. As an initial step toward this long-term goal, this paper addresses the relevance of the geometrical information captured by isovists for mental representations.

In the following subsection, relevant literature regarding isovists and mental representations related to wayfinding is reviewed. In Section 2, we describe the experiment where participants learned and retraced two routes through a photorealistic virtual environment. Here also the methodology regarding isovists and mental representations is introduced. In Section 3 the results are presented. We discuss them in Section 4 with respect to literature both from the domain of spatial analysis and from the area of spatial cognition.

1.2 Space Syntax, Isovists, and Visibility Graphs

Space syntax is a set of technologies for the analysis of spatial configurations using simple graphs solely consisting of paths and nodes [16, 17, 18]. The techniques were developed in the late 1970 in order to analyze interrelations between spatial and social structures. This analytical reduction of space to mere topological mathematical information facilitates the calculation of characteristic values and the quantitative comparison of environments. Originally, space syntax was developed to analyze topological properties of large-scale spatial configurations from the room layout of building complexes to whole cities. Hence, these techniques deliberately abstracted from geometrical detail.

For analyzing geometry-related spatial characteristics of environments, Benedikt [2] proposed *isovists* as objectively determinable basic elements. Isovists capture local spatial properties by collapsing the space visible from a single observation point to its two-dimensional abstraction. From these viewshed polygons, several quantitative geometrical descriptors can be derived such as area, perimeter length, or number of vertices. In a second step, these values can be mathematically combined to get further characteristic values. In order to better describe the geometry and also configurational characteristics of an environment as a whole, Turner, Doxa, O'Sullivan, & Penn [33] have developed the technique of *visibility graph analysis* that combines aspects of global space syntax graphs with local intervisibility information as captured by isovists. Furthermore, this technique lends itself well for computer implementations. Although isovists describe abstract geometrical properties, recent research has shown that isovists are correlated with spatial behaviour and affective responses to indoor spaces [e.g., 10, 32, 35].

Isovists basically describe local geometrical properties of spaces with respect to individual observation points and weight all possible view directions equally. Especially for the analysis of individual motion trajectories, sometimes also view-specific *partial isovists* have been applied [e.g., 4]. Partial isovists consider only a restricted part of the theoretically available visual field (e.g., 90° instead of 360°). They correspond better to the restrictions of the human visual apparatus. Analogously, several studies have shown that humans encode spatial information from the point of view they encounter it [e.g., 3, 6, 11, 23].

Isovists are means to describe aspects of the outside world. As our goal is to reveal a connection between the geometric properties of the outside world and the inside world, we will now look what we store in our heads when walking around.

1.3 Knowledge in Wayfinding

In the wayfinding literature the distinction between *landmark*, *route,* and *survey* knowledge has received a lot of attention [e.g., 12, 15, 22, 27, 30, 31]. Landmarks are salient locations in the human environment such as a church or a square. *Landmark knowledge* refers to the recognition of these locations, e.g., "I know this esplanade, so I've been here before". Landmark knowledge alone is not sufficient to reach a goal. By recognizing a landmark, we know that we are on the right track, this however does not tell us, where to go next. The correct movement decision at an identified location requires route knowledge. *Route knowledge* describes the path that one must walk to reach the goal by telling the individual what to do at the decision points on the route, e.g., turn right at the church, then the second street to the left. It is one-dimensional or "string-like" and does not necessarily involve the knowledge of the exact location of the goal. *Survey knowledge*, in contrast, provides the direction and distance a location is to be found independent from knowing a path which leads there, e.g., the train station is about 300 Meters east from here. It is two-dimensional or "map-like". As survey knowledge is not route specific it will not be regarded further in this paper.

1.4 Predictions

Landmark and route knowledge together with wayfinding performance will be the dependant measures of our study. The different geometries of intersections expressed by isovist measures will be the independent measures of our study. Our prediction is that there is a connection not only between the geometry of intersections and wayfinding performance, but also between the geometry and mental representations, namely landmark and route knowledge.

2 Methods

For the experiment we used a virtual environment displayed on a 220° semi-cylindrical screen. The participants learned two different routes through "Virtual Tübingen" a photorealistic model of the medieval city centre of Tübingen (see Fig. 1, [34]). Directly after learning a route, participants had to find and to "virtually walk" this route with a joystick. After that we measured the acquired landmark and route knowledge with two choice reaction tasks. In order to represent expected directional biases, the isovist analysis made use of partial isovists capturing the perspectives seen when approaching the intersections. We validated this approach in the landmark knowledge task by comparing different perspectives of the intersections. Eleven isovist statistics were used to classify the intersections in two geometrically dissimilar groups. Then we compared the wayfinding performance and knowledge in these two

Fig. 1. The setup for learning and navigating the routes in Virtual Tübingen.

groups of intersections. A second study was based on an analysis of the wayfinding data [25, 26]. This analysis was completely independent from the analysis done in the present study.

2.1 Knowledge and Wayfinding Performance

Participants. Twelve female and twelve male participants, mainly students between 19 and 32 ($M = 24$; $SD = 4$), participated in the experiment. None of them had visited Tübingen before. All selected participants were German native speakers and were paid for their participation. Two of original 26 participants did not complete the experiment due to simulator sickness and were therefore excluded from all subsequent analysis.

Learning the Routes and Wayfinding performance. The participants sat on a chair positioned at the focal point 3.5 meters away from a circular 220° screen (width: 13m, height: 3m), which covered the whole horizontal visual field (see Fig. 1). A pc-cluster rendered the projection for an eye position 1.20 meter above the ground referring to an average eye-height in a seated position. The scene was rendered at a frame rate of 60Hz using 2 x hardware anti-aliasing and hardware correction to display the images geometrically correct on the curved screen. Three projectors with a resolution of 1024 x 768 each projected the pictures.

For learning the routes the participants were passively carried through the environment. The transportation speed was two meters per second corresponding to a fast walking speed. The long route spanned 480 meters and consisted of ten mainly oblique intersections with 23 possible choices (see Fig. 2). Having a length of 320 meters, the short route contained nine mainly orthogonal intersections offering altogether 21 possible direction choices (for a further description of these routes see [24]). The order of presentation of the routes was controlled. During route learning,

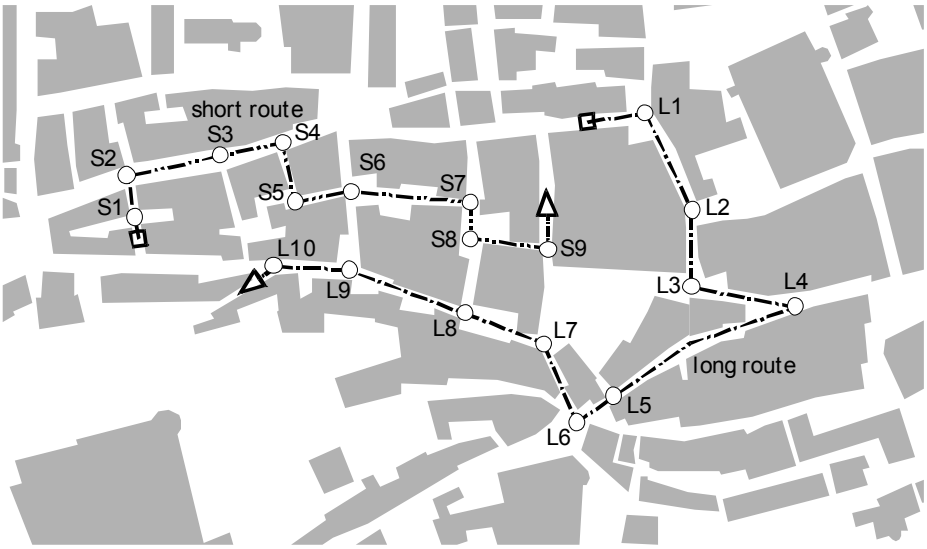

Fig. 2. The two routes through Virtual Tübingen used in the experiment.

participants were confronted with either a verbal, a visual, a spatial, or no secondary task. This aspect of the experiment is described in more detail in Meilinger, Knauff and Bülthoff [25, 26].

No secondary task was applied when the participants actively navigated the routes immediately afterwards. Therefore, all participants had the chance to acquire knowledge without being distracted by a secondary task. During navigation, participants could control their heading and forward translation speed using a customary joystick device. The maximal translation speed was two meters per second. In order to reduce simulator sickness, rotation speed was restricted to 30° per second. The dependent variable *wayfinding performance* was measured by the proportion of correct route choices at specific intersections. When participants chose an incorrect route continuation, they were stopped after about 5 meters by the simulation. In this case they had to turn around in order to continue their navigation.

Before the experiment, participants were familiarized with the virtual reality setup and the joystick-based interaction in an area of Virtual Tübingen not encountered during the rest of the experiment.

Test of Landmark Knowledge. We measured landmark knowledge for intersections in a choice reaction task. Pictures of all intersections sized 1024 x 786 pixel were presented on a screen. In the pictures, the facades of houses situated in front of the intersection were visible (see Fig. 3, left side). Participants had to press a button on a response box as fast as possible to indicate whether they had seen the intersection before. The same procedure was also used to test the perspective bias in recognizing intersections (see Section 2.2). The pictures presented were taken from every street approaching an intersection. So for a four arm intersection, four pictures had to be judged. 61 pictures of intersections and 8 distracters were presented this way. The distracters were pictures taken from intersections in virtual Tübingen not previously

seen by the participants. All pictures were presented in random order. The positions of the hit and reject buttons on the response box were selected randomly for each participant. Accuracy and reaction times were recorded. Extreme values deviating more than three standard deviations from the mean were replaced by the most extreme value observed within three standard deviations.

Test of Route Knowledge. A choice reaction task was used to measure route knowledge. Pictures of intersections were presented, participants had to indicate the correct route continuation by deflecting a joystick in the correct direction as fast as possible (see Fig. 3, right side). In case they were not able to recognize the intersection, they were instructed to deflect the joystick in a backward direction. The pictures used in the route knowledge test phase were identical to the pictures in the landmark knowledge task, but exclusively perspectives along the direction of travel were used. 19 pictures of intersections and 4 distracters were presented this way. Other distracters than in the landmark knowledge task were used that were also pictures from intersections not previously seen by the participants. Pictures and distracters were presented in random order separated by routes. Each picture and distracter was presented twice. Accuracy and reaction times were recorded. The correction of extreme values was identical like in landmark knowledge.

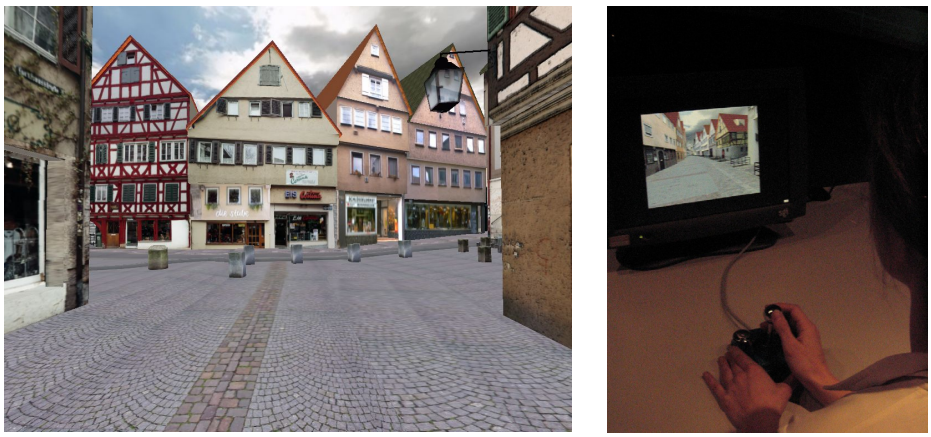

Fig. 3. To measure their landmark and route knowledge, participants saw pictures like the one on the left side. For route knowledge the participants indicated the further route with a joystick as seen on the right side.

2.2 Test of Perspective-dependent and Geometry-dependent Recognition Biases

We wanted to test whether the directed route presentation and exploration in the initial learning phase of the experiment led to a stronger memorization of this particular perspective. Therefore, we analyzed the data obtained from the landmark recognition task (see landmark knowledge) on direction-specific differences. For this purpose, the performance in discriminating a picture of an intersection from a distracter *d'* was computed for each perspective of an intersection [13]. The statistic

d' expresses the difference between the normal distribution of stimuli and the normal distribution of distracters in standard deviations. A *d'* of 1.0 means that the two distributions are one standard deviation apart. If a participant recognized all distracters or targets, *d'* could not be computed. In this case a recognition rate of 100% was replaced by a 99% score. The perspective seen when approaching the intersection was expected to be recognized more easily compared to perspectives in a 90° or 180° angle to this perspective. Reaction times and *d'* in these groups of pictures were compared within-subject using an ANOVA with post-hoc t-tests.

2.3 The Direction-Specific Isovist Analysis

Isovists. The differential analysis between intersections described above required a quantitative description of the individual intersections. In order to test whether expected differences could be attributed to some visuo-spatial properties, a quantitative description of the intersections' geometrical layout and shape based on isovists was calculated. Isovists, as originally conceived by Benedikt [2], equally describe all possible view directions from a given single observation point, a perspective which is directly perceptible only in an unnatural bird's eye view of a spatial environment. In reality, however, observers experience the environment mainly from a directed inside perspective along their main line of travel, suggesting a different weighting of view directions depending on their relative angle to this main direction. In order to account for this in the isovist-based spatial analysis, two specific adaptations were introduced: First, instead of basing the analysis on ordinary 360° isovists, directed partial isovists spanning a horizontal angle of 90° were applied [cf. 4]. Second, in order to include also information on branchings beyond this restricted angle, the reference points of the isovists were shifted from the center of the intersection in the direction the intersection was approached from. Thus the isovists

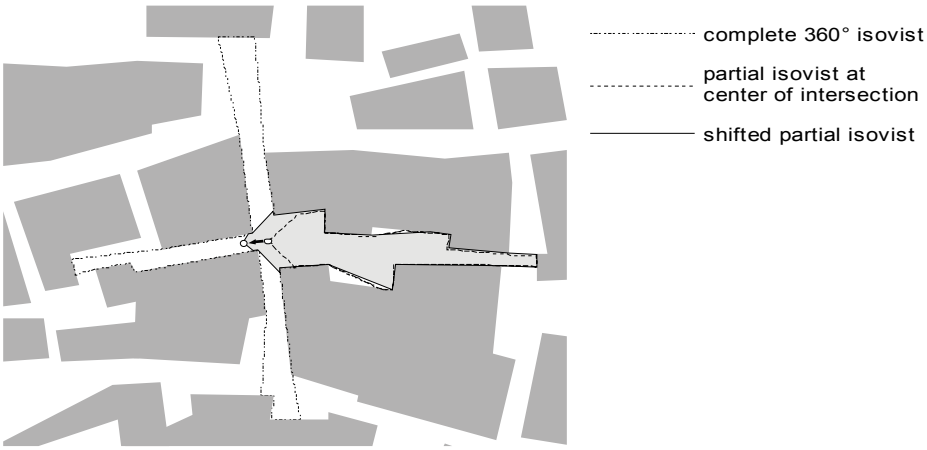

Fig. 4. Exemplary illustration of the applied partial isovist analysis (intersection S6). The analysis accounted for the directed perspective participants experienced the environments. In order to do so the reference points of the partial isovists was shifted into the direction of approach, which is to the left in this example.

corresponded to the visual field as available immediately before entering the junctions. (cf. Fig. 3 left side and Fig. 4.).

The eleven isovist-based geometrical descriptors of the junctions were calculated using the free ajanachara tool [9] which offers both isovist and visibility graph-based statistics. The visibility graph analysis was done at a spatial resolution of 1.5 meters, i.e., squares with 1.5 meters length represented either walls or open space. Table 1 gives a short overview of the individual variables which comprised typical local geometrical measures from the isovist literature. For more detailed information, please refer to Franz and Wiener [8].

Isovist-based Categorization of Intersections. Based on the eleven isovist statistics obtained by the analysis described in the previous section, a measure of geometrical similarity of the intersections was calculated. Since isovist statistics typically correlate highly with each other, first, a factor analysis was applied to identify independent dimensions underlying these parameters [e.g., 1, 21]. A principal component analysis extracted factors with an eigenvalue > 1.0 out of the correlation matrix. In order to do so, the isovist statistics were correlated with each other over the intersections. A multiple linear regressing estimated the communalities. The resulting factor matrix was rotated using the VARIMAX method. Each intersection could be described now by their factor values on three independent factors. A hierarchical cluster analysis grouped the intersections on basis of these factor values using Euclidean distances and the Ward method to compute distances between groups of intersections [e.g., 1, 7]. The last two groups of intersections to be clustered together were taken as geometrically distinctive groups of intersections. To see if participants reacted differently to these geometric layouts, navigation performance, landmark knowledge, and route knowledge on these two groups of intersections were compared with each other in t-tests.

Table 1. Description of the eleven isovist statistics used in the analysis comparing the geometrical characteristics of the junctions.

Isovist Statistic	Short Description
Area	Number of 1.5 m x 1.5 m squares lying with at least 50% inside the isovist
Perimeter length	Overall length of the isovist boundary
Vertices	Number of vertices of the isovist polygon
Vertices per perimeter	Number of vertices divided by perimeter
Vertices per area	Number of vertices divided by area
Roundness	Isovist area divided by squared perimeter length
Jaggedness	Squared Perimeter length divided by area
Bounding proportion	Length of the principal axis of a minimal bounding rectangle divided by its secondary axis
Convexity	Roundness divided by bounding properties. A measure for the deviation of the isovist from a rectangle
Openness	Length of open edges dived by length of closed edges. Closed edges are visible walls, open edges result from occlusions
Clustering	Percentage of pairs of squares in the isovist which can see each other

3 Results

3.1 Perspective-bias in Recognition

To tell whether the perspective seen when approaching an intersection was the most relevant, different perspectives of intersections were compared in the landmark knowledge task. We computed the performance in discriminating the different perspectives of intersections from the distracters. The performances differed due to the angle between the perspective the picture was taken and the direction of traveling (see Fig. 5; *d'*: $F(2, 46) = 29.8$, $p < .001$, $\eta^2 = .56$; reaction time: $F(2, 46) = 12.8$, $p < .001$, $\eta^2 = .36$). Pictures taken along the direction of traveling (0°) were recognized better compared to pictures taken from 90° to that (*d'*: $t(23) = 10.2$, $p < .001$, effect size = 2.08; reaction time: $t(23) = 4.12$, $p < .001$, effect size = 0.84) or taken from 180° (*d'*: $t(23) = 3.84$, $p < .001$, effect size = 0.78; reaction time: $t(23) = 4.42$, $p < .001$, effect size = 0.90). Pictures taken from 90° were recognized worse than pictures taken from 180° (d': $t(23) = 3.05$, $p = .006$, effect size = 0.62; reaction time: $t(23) = 1.15$, $p = .262$, effect size = 0.23).

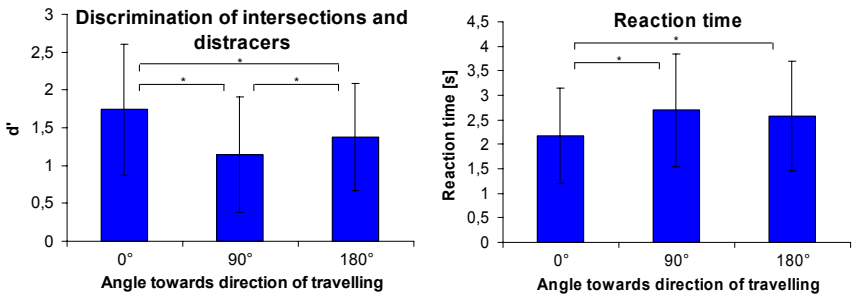

Fig. 5. d' values expressing the performance of differentiation between distracters and pictures of intersections (left) and reaction times (right). The pictures of the intersections were taken from the direction the intersections were approached originally (0°) or from an angle of 90° or 180° to that direction. Means and standard deviations are displayed. Asterisks mark significant differences at $p < .05$.

3.2 Isovist Analysis

We used an isovist analysis to identify two groups of geometrically different intersections and relate them to navigation performance and knowledge measures. The space visible when approaching an intersection was expressed in eleven isovist statistics. A principal component analysis identified three independent factors with an eigenvalue > 1 underlying the eleven highly correlated isovist measures (see Table 2). Geometrically similar intersections show similar isovist statistics and therefore also similar values on the underlying factors.

A hierarchical cluster analysis grouped the intersections successively based on their geometrical similarity expressed in similar values in theses three independent factors. First, very similar single intersections were grouped together. Then, similar

Table 2. The rotated component matrix with the loadings of the isovist statistics on the three independent factors. Grey shading indicate higher loadings. This means that the factor expresses much of the variance of this isovist statistic.

	Factor 1	**Factor 2**	**Factor 3**
Vertices	0,89	-0,11	-0,13
Bounding properties	0,88	-0,24	-0,03
Convexity	-0,76	0,35	0,46
Area	0,67	-0,57	0,18
Perimeter	0,69	-0,62	-0,21
Roundness	-0,65	0,54	0,50
Vertices per perimeter	-0,28	0,92	0,16
Vertices per area	-0,26	0,93	0,01
Clustering	-0,12	0,37	0,84
Openness	-0,01	0,33	-0,82
Jaggedness	0,51	-0,45	-0,64

groups were merged together until in the end only two groups remained before being merged together (see Fig. 6). These last two groups consisted of T-intersections that are the intersections S5, S7, S9, L1, L3 and L4 in contrast to the non-T-intersections. These two groups of intersection differ in the geometry seen when approaching the intersection: At a T-intersection, one sees a wall in front and two route alternatives to the right and to the left. The same intersection would be classified differently when approached from a different direction, as here a street would branch of from a straight main street.

The performance on theses two groups of geometrically different intersections was compared. At non-T-intersections the participants clearly performed better than at T-intersections (see Table 3). The participants recognized non-T-intersections faster than T-intersections ($t(22) = 2.51$, $p = .020$; accuracy $t(23) = 1.21$, $p = .238$). At non-T-intersections the accuracy in indicating the further route was higher compared to T-intersections ($t(23) = 4.71$, $p < .001$; reaction time $t(22) = 0.76$, $p = .457$). At T-intersections the participants got lost more often than at non-T-intersections ($t(23) = 2.56$, $p = .017$). The geometry of intersections was associated not only with different wayfinding performance but also with different landmark and route knowledge.

Table 3. Mean performance (with standard deviations) at T and non-T-intersections and effect sizes for the differences. Asterisks mark significant differences at $p < .05$.

	T-intersections	Non-T-intersections	Effect size
Landmark knowledge			
Accuracy	0.55 (0.20)	0.62 (0.22)	0.25
Reaction time* [s]	2.62 (1.43)	2.22 (1.03)	0.52
Route knowledge			
Accuracy*	0.42 (0.21)	0.61 (0.16)	0.96
Reaction time [s]	2.51 (1.01)	2.41 (0.97)	0.16
Wayfinding performance per intersection			
Getting lost*	0.19 (0.18)	0.12 (0.13)	0.52

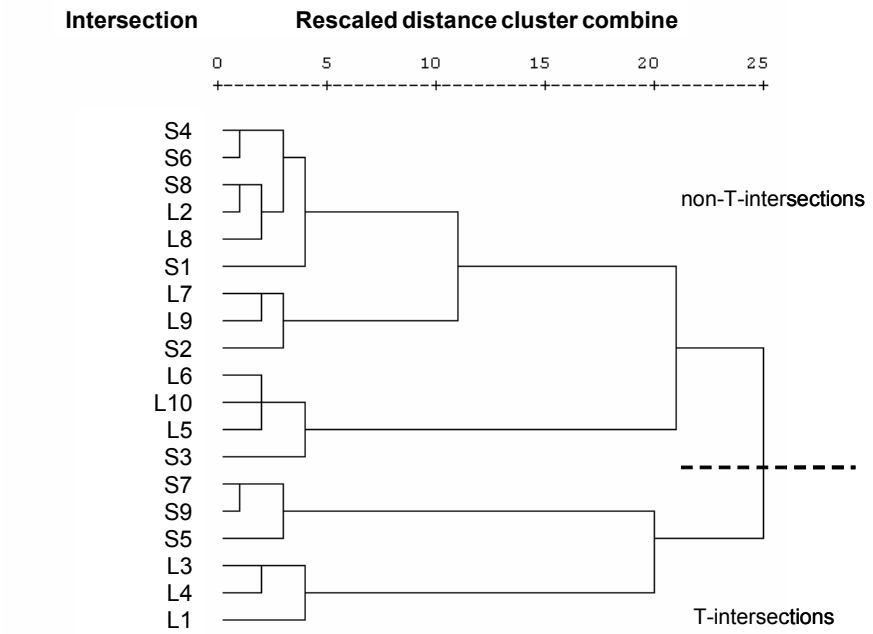

Fig. 6. Dentrogram of the hierarchical cluster analysis. Vertically all 19 intersections of the two routes are displayed. To the right is the Euclidian distance between intersections or groups of intersections in the three-dimensional space created by the three independent factors. Intersections or groups of intersections are grouped together at a certain Euclidian distance. Geometrically similar intersections are grouped at short distances, dissimilar ones at large distances.

4 Discussion

The present study examined the connection between geometrical properties of our environment and mental representations of this environment. The main finding is that geometrical properties are not only connected with directly observable wayfinding behaviour [e.g., 5, 14, 35], but that they are also connected with mental representations of this environment. T-intersections and non-T-intersections were the geometrically most dissimilar subgroups of intersections as revealed by isovist statistics. At T-intersections participants performed worse in the active navigation task as well as in the landmark and route knowledge tasks.

What could be reasons for this difference between T and non-T-intersections? Generally, T-intersections might be geometrically more similar with each other than non-T-intersections which could be branch-offs, cross-intersections or even more complex intersections. A higher similarity might lead to more confusions and therefore to a lower performance in wayfinding as well as landmark and route knowledge (cf. Fig. 7).

Fig. 7. Two T-intersections on the short route. At the left intersection (S7) a participant had to turn to the right or to indicate so in the route knowledge task. At the right intersection (S9) a participant had to turn to the left.

For both route knowledge and navigation performance, the observed better performance at non-T-intersections must be a very robust effect. In both measures, participants had to choose between alternatives. With more alternatives the task gets more difficult to solve by guessing [cf. 28, 29]. At non-T-intersections, the participants had to choose between 2.4 alternative routes in average whereas at T-intersections the participants only had to choose between 2 alternatives. Despite this higher chance level at non-T-intersections, participants performed better, indicating a strong effect even overriding this bias.

A second important point of this study is the inclusion of perspectivity in the isovist analysis. First, we did not apply isovist statistics with a 360° field of view as is most commonly done, but limited the field of view by applying partial isovists [cf. 4]. Second, the isovists' reference points were shifted towards the approach direction. This approach is in accordance with anatomical constraints of the human visual apparatus and directly corresponds to the directional route presentation. It is in accordance with studies showing that humans encode spatial information from the point of view they encounter them, at least for environments not too familiar [e.g., 3, 6, 11, 23]. In addition, we validated this approach by comparing the recognition performance of intersections. Analogous to the directional bias in the analysis, participants recognised intersections best when shown a picture taken along the direction of traveling. If perspectivity did not matter participants should have recognized the intersections equally well from all perspectives. Although the optimal angular size of partial isovists is object to future studies, one important conclusion can be drawn: As captured by the applied method, a T-intersection is psychologically different from a topologically equivalent branch off. This holds true also if the geometry of both intersections is identical.

In order to close the gap between isovist statistics and wayfinding behaviour by accounting for perception and mental representations, the correct consideration of perspectivity seems crucial. The acquisition of mental representations, however, is only one part of what happens in the brain during wayfinding. In order to make use of this information, the brain has to process these representations. Several strategies and heuristics how to process these representations have been proposed, e.g., the least-angle strategy [e.g., 19]. Other strategies like hierarchical fine-to-coarse planning [36]

or sticking to well-known areas as much as possible have been proposed [20]. Based on the outcomes of this study, this multitude of strategies can be complemented by another heuristic which could be informally termed 'when-in-doubt-follow-your-nose'. We compared the performance at intersections where participants had to walk straight on with those intersections which required a turning. Participants recalled these two groups of intersections equally well (see Table 4 landmark knowledge; accuracy: $t(23) = 0.65$, $p = .520$; reaction time: $t(22) = 1.10$, $p = .282$). When asked to draw the routes including *all* intersections, they made less errors at drawing intersections which required a turn than at drawing intersections where the route went straight on ($t(23) = 3.52$, $p = .002$). Despite the equal to better memory for intersections requiring a turn, participants performed better at "straight-on" intersections when they had to decide for the further route. Participants correctly indicated to walk straight on more often than they indicated a correct turn (see Table 4 route knowledge; accuracy: $t(23) = 3.44$, $p = .002$; reaction time: $t(23) = 1.51$, $p = .145$). They also got lost less often at intersections where no turn was required ($t(23) = 3.58$, $p = .002$). We think that participants decided to walk straight on when they did not remember the further route. This 'when-in-doubt-follow-your-nose' strategy can reduce memory demands. Thus, participants only had to store and recall changes in the direction of travel. It was not necessary to recall where to go at straight-on intersections, because here the default strategy of walking straight on applies. In principle, one alternative explanation would be that participants had to walk straight on most of the times and that these results are therefore specific for these routes. This explanation could not hold true as participants had to walk straight on less often (7 times) than they were required to turn (12 times).

We described the 'when-in-doubt-follow-your-nose' strategy for retracing a route and for the memory of a route. The tendency of walking straight on has already been described for exploring an unknown virtual environment [4]. Here participants rather walk straight on than turn at an intersection.

Table 4. Mean performance (with standard deviations) at intersections where to walk straight on or with a turn required. Asterisks mark significant differences at $p < .05$.

	Route goes straight on	Turn required	Effect size
*Errors at drawing intersections**			
	4.4 (2.0)	2.5 (2.4)	0.72
Landmark knowledge			
Accuracy	0.58 (0.26)	0.61 (0.17)	0.13
Reaction time [s]	2.22 (1.11)	2.39 (1.17)	0.23
Route knowledge			
Accuracy*	0.65 (0.18)	0.49 (0.18)	0.70
Reaction time [s]	2.29 (1.06)	2.52 (0.95)	0.31
Wayfinding performance per intersection			
Getting lost*	0.06 (0.09)	0.19 (0.18)	0.73

We presented various results in this paper. When interpreting and generalizing these results, one has to take especially two aspects into account. First, the results may not be interpreted causally. Not only geometry, but also any other environmental property correlated with geometry could be a relevant cause for the observed differences.

Second, the experiment took place in a typical European city centre with lots of different intersections. The results might be limited to such geometrically rich environments. In a typical American rectangular grid like city layout with geometrical very similar intersections, geometry might play a less important role for wayfinding.

5 Conclusions

Confirming the outcomes of many other studies, this paper has shown that isovist analysis is a powerful tool for quantitatively capturing behaviourally relevant geometric properties of environments. Beyond this, the presented study demonstrated for the first time correspondences between mental representations and geometric properties captured by isovists. Furthermore, this paper pointed towards the importance of perspectivity when predicting human behaviour. Although a street branching-off and a T-intersection might be identical in their abstract geometric and topological layout, they are different psychologically: the very same intersection could be a T-intersection and a street branching off, depending from where it is approached. Considering perspectivity, as in the conducted analysis, is one important point when closing the gap between an isovist analysis on one hand and predicted behaviour on the other hand. We are convinced that this gap can only be closed when taking mental representations and processes into account. The authors hope that this approach is a step not only towards closing the gap between space syntax analysis and behaviour but also towards narrowing the gap between architecture and spatial cognition.

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Isovists for Orientation: can space syntax help us predict directional confusion?*

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Abstract. Focusing on its lessons for deriving and using space syntax measures, particularly those related to isovists, this paper explores the potential for identifying spatial predictors of people's orientation performance with a map. Matching a map to a visible scene, to decide in which direction one is facing, is argued to be a fundamental cognitive subtask which arises in a number of contexts beyond mere wayfinding. The challenge for space syntax is to supply readily computed measures that can adequately predict where this task is more difficult than average, based on analysing a 2D map. If this can be achieved then spaces may be automatically assessed for potential orientation difficulty, so that both the map and the environment can be enhanced to include cues to make it easier. We discuss some issues that arise in applying space syntax to this situation, and describe current progress towards this goal.

Keywords: isovists, space syntax, orientation, spatial cognition

1 Introduction

Space syntax research should have much to tell cognitive science concerning factors that predict people's movement in space, and that thus have (often subconscious) influences on the cognitive process of navigation. So far, however, space syntax has been silent on what happens when people stand still. If our focus is on human cognition of space rather than physical motion per se, then we might expect something about the space itself to influence our thinking about it in other ways than merely when wayfinding. For navigation, measures derived from both axial lines and isovists appear to hold strong predictive power in many situations. This is perhaps not surprising since wayfinding decisions are essentially two-dimensional (people can only walk on the ground), and have to consider the whole 2D space in choosing which

way to travel. Yet different aspects of the space may well prove to be more relevant to other spatial behaviours, such as orientation (which we here define as deciding in which direction one is facing), aesthetic preference, subjective sense of safety or danger, tendency to linger in or pass through an area, the relative salience (and hence awareness) of local objects, factors inducing claustrophobia or agoraphobia, and so on. In most cases this may suggest a need to incorporate 3D, as well as 2D, aspects of the space, and hence perhaps new measures that exploit these effectively to predict behaviour.

1.1 Static orientation and maps

The behaviour that we have focused on in our current project is static orientation. Imagine any of these situations: you have just emerged from a bus, tram or subway; or you have just navigated yourself without a map to a point where you now feel less familiar and certain; or you are remotely viewing a current or a historical camera image of an outdoor scene. You have a map with you, and you now have a need to work out which direction on the map corresponds to a specific direction in the space (e.g. the direction in which the photograph was taken, or the location of a specific building). The context of your need to do this may be for further navigation, to identify specific objects or to make other judgments; the point is that various contexts, not only navigation, could lead to this problem scenario [1].

Why is it worth understanding and modelling this particular task? One reason is that its successful performance is critical to the 'legibility' of an environment: the ability for relative strangers to find their way around and feel comfortable doing so. This is important for economic and social reasons, as it encourages visitors to explore and spend money in a city without fear or frustration, yet it does not only depend on the design of the environment itself. Crucially, it also depends on the map (or other information source) that is consulted; where cues on the map can be easily matched to the scene, the task becomes trivially easy. Where this is less true, the task can be hard or even impossible. Future mapping could be better designed to aid this if we could understand - and automatically (i.e. computationally) predict - the locations where more help must be provided. This is why Ordnance Survey, Great Britain's national mapping agency, is interested in this quite fundamental task of matching maps to scenes.

Working collaboratively, we have approached this problem by initiating a series of (desktop-based) experiments. These ask people to indicate the direction in which they are 'facing' as they view an image of an outdoor scene, relative to a map of the area on which their location is marked. This kind of desktop simulation experiment, typical of cognitive science research, allows us to focus in a controlled manner on the key cognitive processes of the task and to exactly control both the scene and map stimuli, purposefully omitting the complex real-world contexts that would add extra 'error variance' to the data.

The initial experiment has attempted to show how people, when forced to rely on the overall spatial structure of scenes (e.g. continuous streets, dead ends, open spaces, large buildings) rather than any specific features of them (which would have to be

specifically symbolized or labelled on a map to be usable for this task), was able to guess their direction of this scene within a map. In order to accomplish that, a simplified 3D model of the southern English city of Southampton was used. Using images from this, the experiment tested a variety of scenes corresponding to 16 different locations of the city, selecting as many different types of environment as possible. (see Figure 1). They included terraced residential streets, commercial and shopping areas, semi-enclosed green spaces and post-war high-density housing schemes (apartment buildings).

Fig. 1. Location of selected scenes in Southampton

An illustration from this first experiment, shown in Figure 2, illustrates the basic problem that participants are asked to solve. Individuals are shown one of the simplified 3D scenes and its respective map with a dot at the centre. Assuming they are standing at the dot (so that they only have to orientate, not locate themselves), individuals are then asked to indicate (by controlling a short revolving pointer around the centre dot, using a mouse) in which direction the photograph was taken.

A moment's reflection will confirm that if standing at a crossroads in a highly regular and enclosed environment, such as a Victorian terraced street network in a British city, the strong symmetry and simplicity of the isovist from that point may have some relevance to the potential difficulty of deciding which street one is looking down, when compared to a less regularly shaped environment. In the latter case one might expect to more easily identify a unique element or shape within the 2D geometry of the scene which, in the absence of any other cues, could be matched to the geometry depicted on the map .

The experiment tested 54 persons on 20 (plus 5 practice) scenes. Response time and angular direction were recorded. From a spatial perspective, the experiment analyzed the visual dominance of each location within its respective environment

using a methodology called *isovist analysis* [2]. The idea was to compare the spatial and behavioural measures, to identify any strong spatial predictors of motionless orientation.

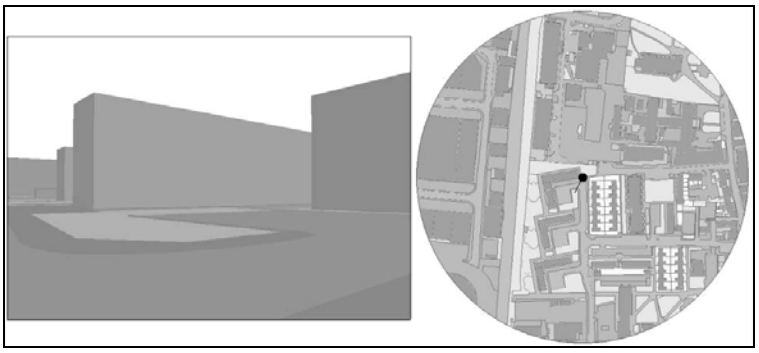

Fig. 2. Sample trial from initial orientation experiment. By moving the mouse over the map (right), the participant moves a line pointer around the marked centre point (centre, the viewpoint of the scene, taken from a simplified 3D model of a real city). When the line reflects the imaginary centre line of the scene image (left), the participant clicks to record a response.

1.2 Isovists and isovist measures

The term isovist has its roots in the seminal work of Gibson [3], who argued that "one can perceive surfaces that are temporarily out of sight" [3:50]. That is, by virtue of motion or deduction people can infer the existence of spaces beyond an isovist's occluding barriers. Although Gibson's work was three dimensional, it later influenced the work of Benedikt [2], who considered isovists as 'regions of space', which can be described by the shapes obtained from people's vision if they rotate through 360 degrees.

Benedikt [2] and Benedikt and Burnham [4] proposed some measures to assess isovists' shapes such as area, perimeter, compactness, skewness and variance, all of which inform the degree to which these polygons are self contained or dispersed in space. All of them refers to a given point x, which is understood as the isovist's origin. Compactness has been mathematically defined by a circle whose radius is equivalent to the isovist's mean radial length, and gives an account of how much the isovist's shape resembles a circle. Variance and skewness describe the degree of dispersion of the perimeter relative to x and the asymmetry of such dispersion respectively. Occlusivity measures "the length of the nonvisible radial components separating the visible space from the space one cannot see from point x", and therefore gives an idea of the degree of 'spikiness' of the isovist.

Benedikt's initial measures were extended by the work of Dalton [5], who proposed the measure of 'drift'. Like the previous measures, drift is a concept defined by the isovist's shape, and describes the vector that links the isovist's origin with its centroid. In addition, recent research by Wiener and Franz [6] has explored the role of isovists

as predictors of spatial behaviour, suggesting the existence of strong correlations between some isovist measures and the way in which space is experienced. Among them the author proposed the measure of jaggedness, which is inversely related to the convexity of the isovist and is formally defined by the ratio between the isovist's square perimeter and its area. A very jagged isovist, therefore, would have 'spikes' that had relatively long perimeters relative to their area, whereas a less jagged one would be closer to circular. The more 'spikes', the more complex the shape of the isovist.

Within the Space Syntax area, more recent work based on isovists has been developed by Turner and others [7,8] who, while trying to give an account of human spatial experience, developed a software package (Depthmap) capable of performing *Visibility Graph Analysis* (VGA). VGA imposes a grid onto a space, and uses it to measure the relative mutual visibility among each of the squares that compose such a grid. A recent application of Depthmap incorporates Benedikt's initial isovist measures but adds 'drift'.

Dalton [5] used a similar VGA technique to test people's navigation in six virtual environments, recording their trajectories, pauses and time spent. They were able to demonstrate from this that pauses do not occur in a random manner but in those places where more visual information is available, usually junctions. In those places the isovists tend to be larger and often spread in different directions, permitting the observer to evaluate the information and to take spatial decisions based on it.

The potential relevance of isovists to orientation was initially suggested by Dalton and Bafna [10] who critiqued Kevin Lynch's [11] assumption that orientation at a given 'node' in a city depended solely on its having a distinctive local landmark. To Dalton and Bafna, isovist analysis might help to "differentiate between nodes that contribute to a sense of orientation and assist in way-finding, and nodes that may confuse or hinder it" [p. 59.13]. This potential has inspired our current work to assess the potential relevance of such measures to people's ability to orientate by matching a scene to a map.

1.3 Some initial assumptions and issues

The nature of isovist analysis depends on a clear definition of opaque boundaries; those are the barriers that would impede vision beyond them. However, when the urban scenes used for the current experiment were initially analyzed, some questions rapidly arose.

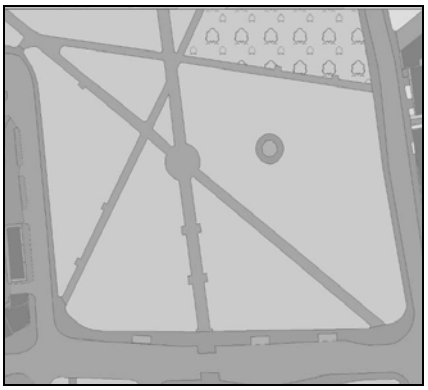

Fig. 3. Different types of opaque boundaries. Here the road surrounding a park is edged both with buildings (dark objects at right and left) and non-building structures such as bus stop shelters (along the bottom). The wooded area at top right is indicated on the map by a generic tree pattern, rather than showing the exact tree locations; all other trees and street furniture are missing.

As can be seen in Figure 3, opaque objects exist both as buildings and non-building structures such as bus stop shelters. While convention suggested that the former were more likely to be considered as an opaque boundary, some questions remained over the latter. Isovist analyses were therefore performed in two scenarios: firstly as opaque barriers formed by buildings and shelters (as if one cannot see through), and secondly considering only the buildings as occluded boundaries (that is, assuming that all other objects are to some extent transparent). The resulting isovists were labelled 'dense' and 'diffuse' isovists, respectively.

In the same vein, it did not seem logical to extend the measured isovist beyond the end of the map (which was circular to avoid giving the user greater information in any one direction and hence biasing the experiment). Information that could not be matched between map and scene could not be used to help the user to orientate, and hence could not affect the performance of the task. Furthermore, it was considered that spatial decisions regarding orientation may rely on more proximal information than on information located at the border of the selected radius. For this reason, the original circle of 400m diameter was halved into a concentric circle of 200m diameter, and the isovist portion within this circle was also measured. Figure 4 shows the results of varying these parameters.

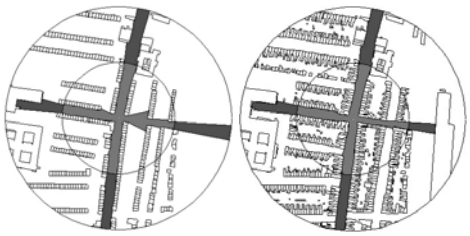

Fig 4. Left: isovist extents at 200m (light grey) and 400m (light+dark) from one sample location, excluding non-building objects. Right: the same isovist, but taking account of non-building structures.

Once the barriers were defined, isovist analysis was carried out using Depthmap version 6.0818, developed by Turner [12]. Assuming that the circle's central point was the origin of the isovist (or person's head), the software traces rays in 360 degrees until each of them encounters an opaque barrier. The result is a specific shape, corresponding to the potential field of view of an individual standing at this location.

Examples for different scenes are shown in Figure 5.

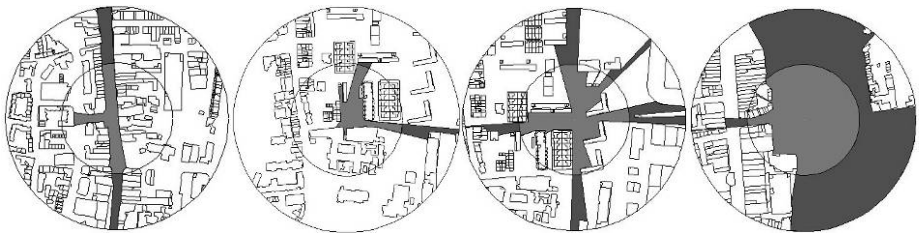

Fig. 5. Some examples of isovists, from left to right: at a location in the city centre; two different points in a post-war residential housing estate; in a city park.

2 Preliminary results

2.1 Isovist measures

This initial study raises a number of important issues concerning the measures. First, it is clear that in less built-up areas the boundaries of isovists became less certain. Even when using a detailed large-scale map such as Ordnance Survey's OS MasterMap®, in the absence of 3D information it is not possible to tell whether and when walls, fences, foliage or street furniture restrict the view. Other factors requiring consideration are the height of the observer and the degree of transparency of borders that might be considered as visual boundaries. An example of this is the location of

five scenes that consisted of views in different directions from the same point, at the side of a road running across one of the city's central parks (the rightmost isovist shown in Figure 5) . Treated as an open space without trees, the isovist almost covers the 400m circle that surrounds it. However, as can be seen in the photographs (upper row of Figure 6), the existence of trees and bushes obscures the perception of distant objects, which appear barely recognisable. Worse, in summer, the distant objects are completely hidden by foliage – so the true isovist actually varies with the season.

The same can be said for the scene shown in the lower row of Figure 6, where the view of a church is partially obscured by a short wall, and by trees which are barely noticed in winter but which overwhelm the view in summer. These examples clearly illustrate the important issues of realistically accounting for significant foliage, and for apparently minor architectural features such as walls and fences.

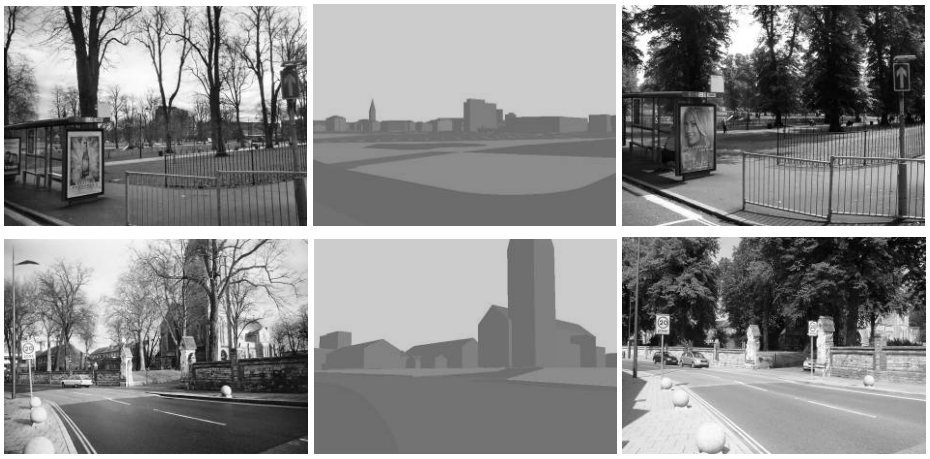

Fig. 6. Two of the Southampton locations, as photographed in January and in June 2006. Middle images show the same scenes but taken from a buildings-only 3D model (overlaid on OS MasterMap® Topography Layer, draped on an OS Land-Form PROFILE® terrain model).

The initial analysis revealed very low correlations among the measures. Even measures that are normally well correlated, such as Area and Perimeter [4, 5, 7], did not show correlations above .25, neither for diffuse nor dense isovists calibrated for either 200m or 400m. Higher correlations were found between Jaggedness and Compactness, although these measures are themselves very similar due to their dependence on the isovist's perimeter. To determine whether these low correlations were due to the specific features of the five park scenes, because of the location's near-circular isovist, these scenes were removed from the sample. This resulted in a markedly increased correlation between Area and Perimeter, and also among several other measures (shown in Table 1).

Table 1. Correlations among the scene isovist measures

"Dense" isovist, radius 400		Without park location						
		area	perimeter	occlusivity	drift angle	drift magnitude	compactness	jaggedness
With park location	area		**0.75**	0.69	0.01	0.17	0.12	0.18
	perimeter	**0.21**		0.78	0.00	0.31	0.52	0.66
	occlusivity	0.00	0.36		0.04	0.07	0.28	0.43
	drift angle	0.12	0.10	0.13		0.13	0.04	0.02
	drift magnitude	0.05	0.18	0.03	0.01		0.19	0.25
	compactness	0.66	0.02	0.13	0.04	0		0.87
	jaggedness	0.27	0.17	0.14	0	0.02	0.74	

The correlation between Area and Perimeter for 400m isovists, both diffuse and dense, was much larger (.76 and .75 respectively) than that for 200m radius isovists (.56 and .2 respectively). In general, both for the 'dense' and 'diffuse' isovists, more correlations were found among the measures when using the 400m than the 200m diameter, owing to the greater proportion of 'artificial' (circle-bounded) perimeter in the latter.

Meanwhile, there was little difference in most measures between the 'dense' and 'diffuse' isovists, partly because most non-building structures recorded in the OS MasterMap® data were either behind buildings and hence invisible from the street, or were too sparsely distributed to be a frequent feature of the scenes.

2.2 Isovist and behaviour measures

Correlations among isovist measures have important implications when one is trying to build them into a predictive model of behaviour. Ideally we would predict outcomes as well as possible, by taking as few measurements as possible. Where two measures closely correlate, therefore, it implies potential redundancy – one can (and should) probably be dropped from a predictive regression model to avoid overspecification.

With this in mind, initial analyses of the data have focused on optimising a multiple regression model to explain the number of participants responding correctly to each scene (within 30 degrees, i.e. within the visible scene). This analysis should be viewed as tentative, since it is based on only 20 scenes. However, the dependent variable (number of participants performing correctly) probably had low measurement error, being based on 54 participants and showing a close fit to a normal distribution.

As with all such analyses, the issues faced in inspecting and evaluating the variables prior to the regression are an important part of the lessons we can learn about the study. In this case, two of the street scenes tended to have particularly low

rates of correct response (18 or 20 out of 54), and thus formed outliers that could severely distort the apparent relationships between the independent (predictor) and dependent (behavioural) variables. At the same time, as mentioned above, the open space of the five park scenes also showed quite different patterns of correlations among the predictors, although it had no apparent consistent effect on people's performance. It is difficult under such circumstances to decide which scenes, if any, to exclude from analysis; such issues would probably disappear if a much larger number of scenes was included that varied the extent of open space and the number of appropriate cues available for solving the task (which appeared to be the problem for the two lowest-scoring scenes).

Other issues which have to be tackled for a meaningful regression model are linearity; relationships between variables are not always a straight line. For instance, as well as isovist-related measures, our analysis also includes the bearing (angle) from north of the correct response, since previous studies (e.g. [13]) have shown that this has a curvilinear relationship to orientation performance in simple environments when the map's north-up orientation does not match the direction of vision. Such relationships need to be handled by applying transformations to variables, or by using more sophisticated regression models.

To date, a great deal of variation has appeared when choosing different methods and criteria for running a multiple regression using the set of isovist measures (plus angle of correct response) as independent measures. Jaggedness appears to be a fairly significant predictor, regardless of the form of analysis chosen; most other isovist measures tend to cause collinearity or show low correlations with people's orientation performance. As explained earlier, jaggedness is a measure that ultimately reflects the isovist's shape complexity, and therefore high jaggedness implies that there is more environmental information available to be used in spatial decisions. Further analyses are continuing.

Meanwhile, in separate qualitative analyses we have been investigating the apparent strategies used by participants to solve the orientation task. Initial tentative conclusions suggest that the role of isovists may always be limited, since most people seem to pick out a single conspicuous feature and match that to the map, rather than deducing the overall isovist. However, often the 2D scene geometry is the best 'feature' available for this, so it is still likely to play some part in people's solutions under some circumstances.

3 Discussion

This research seeks to answer a fundamental question concerning the application of VGA to the information used by people orienting themselves in the environment, but this experiment has revealed a number of complicating factors. Although it may be expected that orientation decisions are typically taken based on proximal (nearby) information, from the point of view of an isovist analysis it seems more realistic to include the largest area possible, in order to simulate the field of view of an observer. This is especially relevant in this experiment, where no contextual clues (cars, street furniture, shops) are observable. In fact, it seems likely that several judgments were

based on the spatial structure of the scene (in the absence of distinctive individual features that could be matched), which may be easier to use when more extensive isovists are seen. However, we have seen that in real environments distal cues are more likely to be obscured by non-mapped objects such as street furniture and trees, suggesting that a more restricted isovist could be more realistic. At the same time, features that are not shown on a map cannot help with orientation performance – but restricting the isovist to the extent of the map introduces an artefact into its shape.

Further artefacts, of course, arise due to the nature of this initial experiment. These include the way that the task required rotating a single pointer (while not being able to rotate the map), matching the scene's centreline (rather than its extents or specific objects), and being able (to a limited extent) to match colours between the scene and map (while not being exposed to the same number of depth cues as in real spaces). These limitations on generalisability are now being addressed through further experimental work. However, we are confident that the same basic cognitive processes are involved in matching the scene to the map under any circumstances where the abstraction of the 2D geometry from the 3D scene is necessary (that is, whenever other cues such as labelled landmarks or street names are unavailable or ambiguous on the map).

Another apparent artefact is actually often a factor in real-life situations. It may be desirable to distinguish the 'forward facing' part of the isovist from the total 360-degree view, since people tend not to rotate (or may not be able to, as in the above experiment, or for example when driving a car or viewing a photograph). It is possible that certain aspects of the task are predicted by measures of the partial isovist indicated by the scene image (which in the case above covers a 60 degree angle – 30 degrees either side of the centreline), while other aspects are better predicted by the overall isovist, for example the extent of the ambiguity in interpreting potential directions from the map. We are currently working to investigate how these two levels of isovist relate to each other, with respect to predicting participants' behaviour in the orientation task.

The park example given earlier raises important questions concerning the application of VGA to open, semi-natural spaces, where 'complexity' in VGA terms may be far less closely related to the distinctiveness of the different vistas. Open spaces, when considered treeless, are transformed into near-infinite isovists, although this is far from true in the real world. It seems therefore that isovist analysis requires well-defined borders in order to be realistic, which only occur in built-up areas. Similarly, terrain (e.g., hills, terraces and landscaping) are not taken into account in standard VGA (although this made little difference in the current case because Southampton is relatively flat).

Furthermore, even when 3D data is available that may help to define the isovist in terms of building and terrain constraints, it is quite possible that it may be incomplete (e.g., not including street furniture) or out of date (due to building demolitions, additions and alterations). These issues arose with the 3D model and map used in the current study, even though they were both created within the past three years. We believe that analysts may need to start to take these issues into consideration when applying isovists in real-world scenarios.

This article has been prepared for information purposes only. It is not designed to constitute definitive advice on the topics covered and any reliance placed on the contents of this article is at the sole risk of the reader

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Architecture of Mind and World
How Urban Form Influences Spatial Cognition

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Abstract. Spatial cognition studies the interaction of people and their surroundings from a theoretical perspective, whereas urban design focuses on creating those surroundings and ensuring that they are liveable. This study bridges the two disciplinary worlds by evaluating undergraduate's spatial knowledge of their college campus and relating that to the urban form of the campus. Participants' performance on two tasks of spatial judgment and memory, a pointing task and a map arrangement task, reveal systematic distortions, presumably the result of simplifying heuristics. These distortions are strongly correlated with the urban form of the campus. To formally describe the campus, I use a set of computational techniques from architects and urban planners known as space syntax. The particular case study of this one college campus does have issues, as I discuss. Regardless, this study demonstrates how our spatial knowledge is intimately linked with the design of our surroundings, which lends real-world support to spatial cognition research and suggests that that theoretical work can be of practical use to urban designers.

1 Introduction

We all require spatial knowledge of our world in order to travel to the grocery store and back, in order to answer such questions as Which is further west, Reno or San Diego?, and in order to provide route directions to visitors from out of town. How we acquire, store, and use this knowledge is of central interest to the field of spatial cognition. Many people spend the better part of their day in a built environment, i.e. the urban world (with varying density) of buildings, streets, parks, parking lots, blocks, and squares that has been designed and constructed by humans. Therefore, much of their thought about space (spatial judgment and memory) and movement through space (locomation and wayfinding) is directly

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intertwined with the architectural and urban form of their surroundings. How does the form of peoples urban surroundings affect their spatial knowledge of those places? In particular, how does urban form affect spatial judgment and memory?

Studying the effects of urban form on spatial cognition requires a formal system for describing the built environment. Space syntax, a set of techniques for analyzing the configuration of building interiors as well as urban environments, allows for such a computational characterization (Hillier and Hanson, 1984 is considered the seminal work). This study will pair these space syntax analyses with behavioral data on spatial judgment and memory tasks.

1.1 Cognitive Maps, Spatial Judgment, and Spatial Memory

The term *cognitive map* effectively refers to the mental representations that store a persons spatial knowledge of an environment. However, the term is notoriously ambiguous–the form it takes on differs from theory to theory. Cognitive maps may be considered to be actual metric maps, map-like in form, acting like maps in practice, or convenient fictions (see Kitchin, 1994). For the purposes of this study, which focuses on performance in spatial judgment and memory tasks, I adopt the last view and simply consider a cognitive map to be one's spatial knowledge of an environment. According to this perspective, a cognitive map is shaped by a number of different processes that do not necessarily follow the constraints of physical maps.

Just as with most other processes of human thought, spatial cognition involves the use of heuristics. Tversky (1981) identified a set of basic heuristics that are used to encode and store memory of environments and maps, as well as of meaningless visual forms. "Remembering the absolute location of figures is difficult, and is facilitated by remembering locations relative to other figures and/or relative to the natural directions of the figure" (Tversky, 1981, p. 407). This simplification process is revealed in systematic errors, which Tversky attributes "to two heuristics that are derived from principles of perceptual organization" (1981, p. 407). The *alignment heuristic* predicts that "two figures that are perceived as grouped together but are misaligned, that is, offset in one spatial dimension, are remembered as more aligned than they really are." The *rotation heuristic* assumes that "figures are remembered with respect to a frame of reference [e.g. north-south, east-west], and that, when the orientation of the frame of reference and the natural orientation of the figure conflict, the figure's orientation will be remembered as closer to that of the frame of reference" (Tversky, 1992, p. 136). Note the connection to perceptual processes: rotation "is similar to the Gestalt organizing principle of common fate" and alignment "is related to grouping by proximity" (Tversky, 1992, pp. 135-6). These heuristics have been demonstrated to apply to the spatial judgment and memory of large-scale spaces, such as continents, more local spaces such as streets, and both real and artificial spaces that are learned through graphical representations like maps (see Tversky, 1992 for a review).

These alignment and rotation heuristics as well as other processes involved in spatial cognition lead to systematic errors in spatial judgment and memory (see Tversky, 1981, 1992 for reviews). For example, many incorrectly believe that San Diego is west of Reno, Nevada, due to the hierarchical grouping of cities within states and the subsequent alignment and rotation of the states. Tversky (2003) suggests a number of reasons that these errors exist. Cognitive processes schematize spatial information so that it can be represented and stored for future use. This schematization allows for integration of disparate knowledge from different sources and different perspectives as well as optimization of that knowledge so as to reduce the load on working memory. In the process of optimizing spatial knowledge, little metric information, e.g. distances, is precisely retained or preserved in whole. My proposal that the form of an environment is intimately connected with the form of its mental representation suggests that the use of these heuristics depends upon the configuration of the environment. The identification of systematic errors in spatial judgment and memory under specific conditions can be used to indicate the involvement of the alignment and rotation heuristics.

1.2 Space Syntax: Computational Analysis of Urban and Architectural Form

As previously mentioned, space syntax provides us with a set of techniques for producing an abstract model of the configuration of a building interior or a part of an urban area. The spaces in question are formally described in terms of their topology—in other words, in terms of the spatial relationships among those spaces, such as connections and adjacencies. Research in space syntax proposes that these models can represent and allow for analysis of salient social and cognitive aspects of building interiors and urban areas (Bafna, 2003). (For more on the philosophical assumptions of space syntax approaches, see Hillier and Hanson, 1984, and Hillier, 1996.)

This topological description takes the form of a graph indicating nodes and their interconnections. In one space syntax technique, *axial map analysis*, each of these nodes stands for a continuous line of sight in the environment. On the campus of Carleton College, one such sightline is the view down Winona Street running into Laird Hall (see the campus map in Figure 4). Such sightlines are commonly referred to as *axes* and a set of interconnected sightlines are called an *axial map*. As shown in the example of Figure 1, axes connect the various regions enclosed by obstacles, such as buildings that would block someone from seeing or walking through.

When creating an axial map, the researcher attempts to draw "the longest straight line that will pass through the boundary between two adjacent regions of the environment in question (Bafna, 2003, p. 23). Thus the axes will connect with each other, forming a graph such as the one shown on the right side of Figure 1.

These graphs retain the topology of the axes—that is, the connections among the axes—but discard all metric information such as the length and angle of the

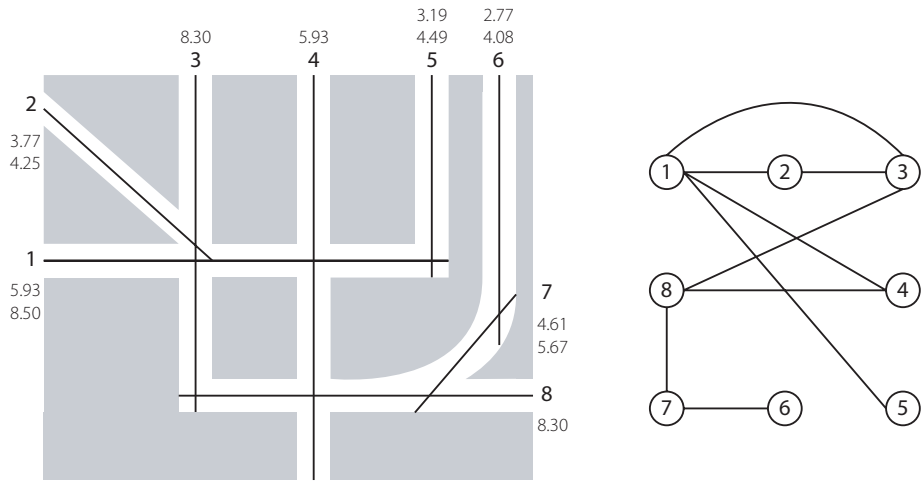

Fig. 1. In this bird's-eye view map (left), axes (black lines) represent sightlines bounded by the gray areas, which cannot be traversed or seen through. Each of the eight axes is numbered (bold type) and its integration values are given (light type) with global integration given before local integration. One number is listed in cases where the global integration of a node is equal to the local integration. This graph (right) shows the connections between the axes, labeled by the same numbers. The metric information such as the length of each axis has been discarded, while the topology of the axes is retained.

axes. "The underlying intuition is based on the notions that first, the line of sight is a significant organizing and unifying device in experience and that second, the number of distinct turns on a route are more crucial to spatial experience than actual distance covered" (Bafna, 2003, p. 23).

This "intuition" is in agreement with research in cognitive science. First, sightlines are a key component of J. J. Gibson's ecological theory of perception (see especially Gibson, 1979, Chapter 11). His "vistas" are centered by a person as opposed to the environment—your vista changes as your location changes—but both vistas and axes emphasize that at a particular moment in time we are presented with a limited view of our environment. When we move, our view progressively changes to reveal new regions, at the same time as we leave behind our most recent view. Our visual experience of the world is defined by this serial sequence of limited views.

Second, humans have been shown to be poor at estimating the metric distance of even the most familiar route or the angle formed by the best-known street intersections. Byrne (1979) has demonstrated that when people approximate distances, they rely on a heuristic that only considers the number of turns made on the route. When approximating the angle of street intersections, people are most likely to approximate the angle as nearly orthogonal (at right angles) or

at 45-degree angles, a finding that suggests they are using Tversky's rotation heuristic.

Once an axial map has been created, measures can be performed on the graph of the axes. One such measure is *global integration*, which quantifies how well individual nodes (axes) are interconnected with the graph as a whole (the map) by calculating the average number of steps required to reach each node from every other node in the graph. Since highly integrated nodes can be quickly reached from many other nodes in the graph, they are described as "shallow," while less highly integrated nodes are "deeper" in the graph. (Note that integration values are customarily reported as inverses, and so larger numbers reflect higher integration.) In the example of Figure 1, Axis 3 has a high global integration value (8.30) while Axis 6 has a low global integration value (2.77). In Figure 1 it can be seen that Axis 3 is more highly integrated with the other nodes than Axis 6, which can only be accessed by way of Axis 7 and Axis 8.

While global integration measures properties of the graph as a whole, local integration only considers the connections among nodes in the context of their immediate surroundings. Local integration is usually computed with radius 3—that is, only nodes within a radius of 3 are used when computing the integration for a particular node. Local integration values are given below each global integration value in Figure 1.

Integration measures have been found to accurately quantify various aspects of human behavior in the environment in question. Bafna (2003) cites studies in which the integration value of an axis in an urban setting was a significant predictor of the average number of pedestrians in that location—the higher the integration, the more pedestrians present. Haq and Zimring (2003) demonstrated such measures to be strong predictors of wayfinding behavior (where people walked) and abilities (how well they performed on assessments of their knowledge) inside large buildings, such as hospitals. Kim and Penn (2004) found that the integration values of street maps sketched by people correlate with actual integration values of the streets. In particular, local integration in the sketch maps correlated highly ($r = .728$) with local integration in the actual map. In other words, participants' spatial knowledge of the environment, as represented in their sketch maps, accurately represented the axial properties of the real world.

The space syntax measure of integration is closely associated with the concept of legibility proposed by Lynch (1960): "the ease with which [the cityscape's] parts can be recognized and can be organized into a coherent pattern. Just as this printed page, if it is legible, can be visually grasped as a related pattern of recognizable symbols, so a legible city would be one whose districts or landmarks or pathways are easily identifiable and are easily grouped into an over-all pattern" (p. 3). In the case of axial map analysis, such an overall pattern takes the form of a graph of axes. Integration measures how tightly each axis is knit into local groups (local integration) and the map as a whole (global integration).

1.3 Connecting Spatial Cognition and Space Syntax

Space syntax research suggests that places with certain configurational characteristics (i.e. higher integration) are used more frequently and by more people, are recalled more often by people, and are more accurately represented when recalled (Kim and Penn, 2004; Haq and Zimring, 2003). Spatial cognition research suggests that people perform better on spatial judgment and memory tasks for places that can be accurately schematized and integrated with other spatial knowledge (Tversky, 1981, 1992, 2003). I propose that there is an intimate connection between these features of the built world and of spatial judgment and memory. Accordingly, space syntax measures, such as integration, should predict performance on spatial judgment and memory tasks.

I will test this conjecture with a real-world case study using the campus of Carleton College and a set of undergraduate volunteers. I will perform an axial map analysis of the campus and ask participants to complete a set of spatial judgment and memory tasks. In particular, I hypothesize that:

1. These space syntax measures will predict participants' performance on spatial judgment and memory tasks. That is, the integration value associated with particular areas of the case study environment will predict participants' performance when they are asked questions about those areas.
2. Since the underlying form of spatial knowledge is presumably consistent across people, demographics (the sex and class year of participants) will not affect performance on spatial judgment and memory tasks. Previous research (Dara-Abrams, 2004) indicated no significant differences in performance on any of the tasks to be used in this study between underclass students (six or fewer trimesters on campus) and upperclass students (seven or more trimesters on campus). In addition, other research (German, Kail, and Siegel, 1979) has shown that undergraduate students become familiar with much of their campus within three months (approximately one trimester) if not within three weeks. However, using extreme groups will, it is assumed, conclusively demonstrate that experience is not a confounding factor.
3. Individual differences in spatial ability will affect performance on spatial judgment and memory tasks. To measure these differences, I will use the Mental Rotation Test (Vandenberg and Kuse, 1978).
4. Systematic distortions, as described by Tversky (1981, 1992), will be observable in participants' responses on spatial judgment and memory tasks.
5. Participants' performance on one spatial judgment and memory task will correlate with their performance on another task, as the tasks are designed to make use of the same spatial knowledge.

2 Method

2.1 Participants

A total of 32 undergraduate students at Carleton College were recruited to participate in the study. An equal number of first-year and senior-year students

were sought, with equal gender balances in each group. All participants were 18 years of age or older and signed informed consent forms at the beginning of their experiment session. They were compensated for their time with gift certificates.

2.2 Instruments

All participants completed four instruments contained in a computer program. Instructions were provided with each instrument. Participants used a Web browser to access the program, which was designed as a Flash movie with Macromedia Flash MX 2004 Professional. The movie files were made available with a Web server running Apache 2 on Windows XP. Also on the server was a script (coded in PHP 4) to process the data entered by participants in order to store it in a database running on that same server (MySQL 4).

Demographics Questionnaire (DG) This questionnaire collects basic information on the background of participants: the number of terms that they have been enrolled on campus in Northfield, the location on campus where they have lived, etc. No confidential or private information is collected.

Mental Rotation Test (MRT) A Mental Rotation Test, MRT, (Vandenberg and Kuse, 1978) is used to assess participants' spatial abilities. After receiving instructions, participants are given three minutes to complete as many of 10 MRT problems as accurately as they can. (See Figure 2 for an example. Scores are based on the number of problems answered correctly, with possible scores ranging from 0 to 10.

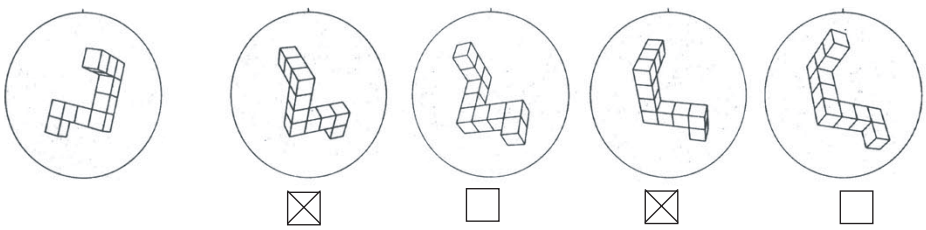

Fig. 2. An example of a problem from the Mental Rotation Test (Vandenberg and Kuse, 1978). Participants are presented with a block figure with a particular orientation (far left) as well as four other illustrations of block figures. Two of these figures have the same structure as the given figure but have been rotated—the task is to identify and mark these. The other two figures have different structures. The correct answers have been marked on this example.

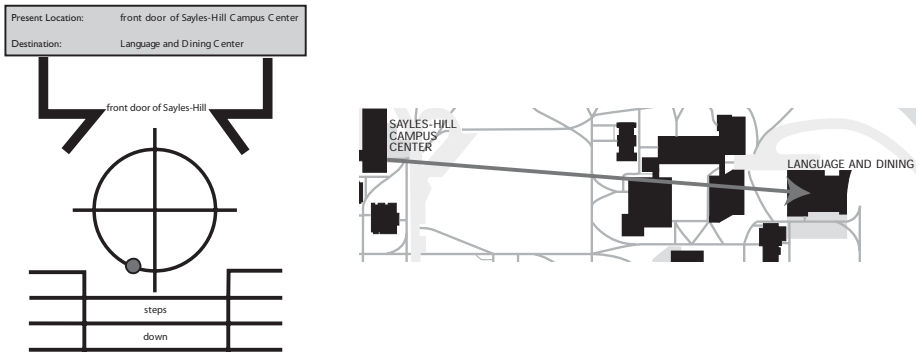

Fig. 3. On the computer-based pointing task, participants are asked to imagine they are standing at a given location, which is represented by a schematic birds-eye view (left), and to then rotate the pointing dot around the compass rose until it points toward the given destination. For the purposes of this example, the correct answer is displayed on a map (right). All participants were familiar enough with the campus to be able to derive the given location and orientation from the details of the schematic drawing.

Pointing Task In the pointing task, participants are asked to judge and record the relative angle between two buildings, given a pair of well-known buildings on the Carleton campus, which are drawn from the list of buildings in question. (Over 90 years of techniques for assessing directional knowledge, including this pointing method, are reviewed and critiqued by Waller, Beall, and Loomis [2004].) All participants are given the same location pairs in the same order. Participants select the desired angle by rotating a pointer dot around a compass rose until it indicates the appropriate direction. The final angle selected is recorded by the software. (See Figure 3 for an example.)

Map Arrangement Task To complete the map arrangement task, participants are given a blank screen, which has been scaled to the size of the standard campus map, as well as a set of similarly scaled cutouts of the campus buildings on the list of buildings in question. Participants are instructed to place the cutouts (which are labeled with building names) in the scaled blank area by dragging and dropping so that the cutouts best approximate the actual orientations and locations of those buildings; participants are allowed to move and rotate the cutouts until they are satisfied with the final arrangement. The software records x- and y-coordinates and rotation for each cutout, so that the arrangement of cutouts can be recreated and so that the angles between buildings can be determined with the use of trigonometric functions. [1]

[1] Interactive examples of the pointing and map arrangement tasks are available on-line: http://drew.dara-abrams.com/research/. Please contact me if you are interested in making use of these tasks in your own work.

2.3 Procedure

Space Syntax Analysis of the Campus The experimenter began by analyzing the urban configuration of the Carleton campus using space syntax techniques. To prepare for the analysis, I manually marked axial lines to represent walkways on a CAD (computer-aided design) map of the campus. (AutoDesk AutoCAD 2004 was used for the initial drawing, with touch-up performed in Adobe Illustrator CS.) Axial map analysis was then used on the resulting map using the software package DepthMap (Depthmap; see Turner, 2001, 2004) to determine the global and local integration values of the axes.

Selection of Building Pairs Based on the resulting patterns of deeper and shallower areas of campus, the experimenter selected 12 pairs of buildings with contrasting integration values to use for questions on the pointing task (see Figure 4). All of the buildings used in the pointing questions also appeared as cutouts for the map arrangement.

Experimental Sessions All participants began by completing an informed consent form followed by the DG and then the MRT. The order in which participants received the pointing and map arrangement tasks was counterbalanced to remove the potential influence of practice effects.

Data Coding Performance on the pointing and the map arrangement tasks is measured by error in degrees. In the case of the pointing questions, error is simply the difference between a participant's response to an angle-measure question and the true angle. The mean of the error on all 12 questions is considered to represent a participant's performance on the pointing task. In the case of the map arrangement task, error is computed to be the difference between the true angle and the angle measured between the pair of building cutouts on a participant's cutout arrangement (computed from the cutouts' x- and y-coordinates with trigonometric functions). The orientation of the building cutouts is not considered.

3 Results

I will describe this study's results in terms of the five hypotheses previously discussed. All statistical tests used an alpha level of .05.

3.1 Demographic Effects

The question is whether participants' performance on the spatial judgment and memory tasks is a property of their particular background or rather an effect of the processes involved in spatial knowledge that are presumably common to

all. If the latter is in fact the case, the findings of this study will have broader implications.

As shown by a factorial analysis of variance (ANOVA), participants' mean error on the 12 pointing questions was not significantly affected by their sex or class year. Males' mean error (M = 33.833, SD = 11.263) did not differ significantly from females' (M = 37.224, SD = 18.555). First-year students' mean error (M = 37.057, SD = 9.156) did not differ significantly from seniors' (M = 34.000, SD = 19.709). The order in which participants took the two tasks did not affect their performance. The only significant effect identified by the ANOVA was an interaction between sex and class year, $F(1, 24) = 4.805$, $p = .038$.

No significant demographic effects on performance have been detected, suggesting that all participants are relying on a common form of spatial knowledge.

3.2 Individual Differences in Spatial Ability

While demographics do not directly affect performance on spatial judgment and memory tasks, I have suggested that there may be individual differences in spatial ability that do. Do participants' MRT scores actually predict their performance on the tasks?

MRT score does not predict participants' mean error in degrees on the pointing questions according to regression analysis, $\beta = -2.153$, $t(30) = -1.633$, $p = .113$. However, MRT score does significantly predict participants' mean error in degrees on the same 12 building pairs on the map arrangement task, $\beta = -4.717$, $t(30) = -3.311$, $p = .002$, and explains a significant proportion of variance in mean error, $R^2 = .274$, $F(1, 30) = 10.964$, $p = .002$. (Note that the MRT score for one female first-year student was thrown out due to improper recording.)

Thus, the MRT does reveal individual differences in spatial ability on the map arrangement but not the pointing task, suggesting that the two tasks make use of difference processes.

3.3 Systematic Distortions

Participants' use of the rotation and alignment heuristics should be apparent in systematic distortions in their responses on the two tasks.

The correct angles for the 12 pointing questions are displayed as dashed lines in Figure 4, with the arrows pointing from the starting location to the given destination. The solid lines display the same angles after they have been rotated by the mean error in degrees aggregated among all participants. That is, the solid angles stand for the average response by participants. For example, participants incorrectly place West Gym to the northwest of Musser Hall. This may be due to the fact that West Gym is on the west side of Highway 19 and Musser Hall is on the east side—if the highway is orthogonalized to north-south, in keeping with Tversky's rotation heuristic, participants will be led to the incorrect northwest response, since West Gym is shifted to the west as the highway is rotated counterclockwise.

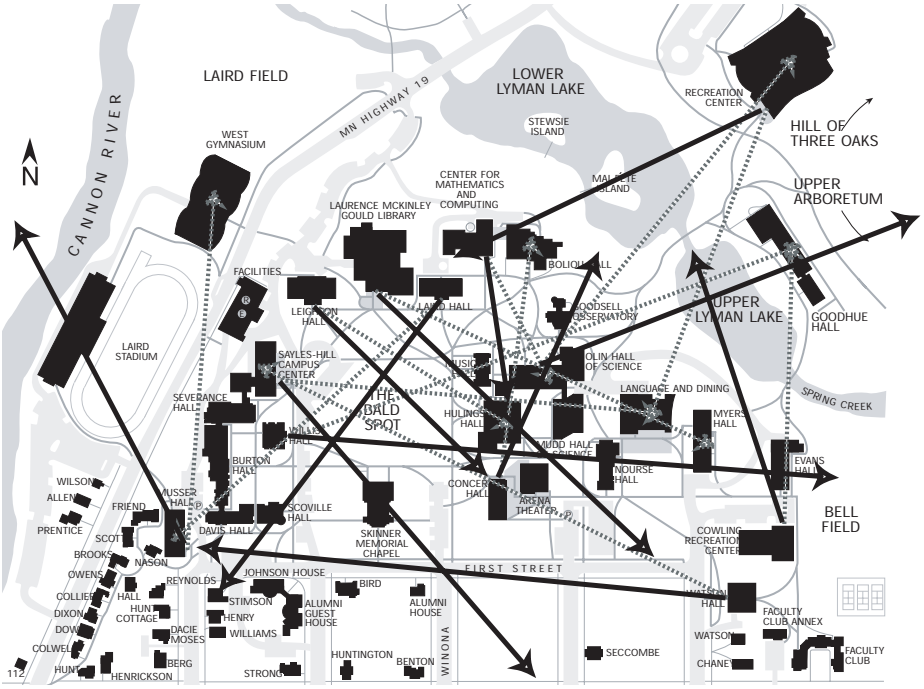

Fig. 4. True angles for the 12 pointing questions are given in gray. Black arrows are adjusted to display the mean error made by participants. Note the systematic distortions, particularly the movement of West Gym, Goodhue Hall, and the Recreation Center.

Such systematic distortions are more apparent in participants' responses on the map arrangement task. For example, Figure 5 shows one participant's arrangement of the cutout pieces, which is representative of many of the responses. Note the use of the rotation and alignment heuristics—the buildings have been arranged in orthogonal lines.

The prevalence of these systematic distortions appears to confirm the use of the rotation and alignment heuristics by the participants when completing the spatial judgment and memory tasks.

3.4 Agreement Between Instruments

If the two tasks ask participants to make use of the same spatial judgment and memory processes, one's performance on the pointing task should correlate highly with one's performance on the map arrangement task. Mean error in degrees on the 12 pointing questions significantly correlates with mean error for the same building pairs on the map arrangement task, $r(30) = .492$, $p = .004$, supporting the conclusion that the tasks are fundamentally similar. This finding is in contrast to the regression analysis showing that MRT score predicts performance on the map arrangement but not the pointing task.

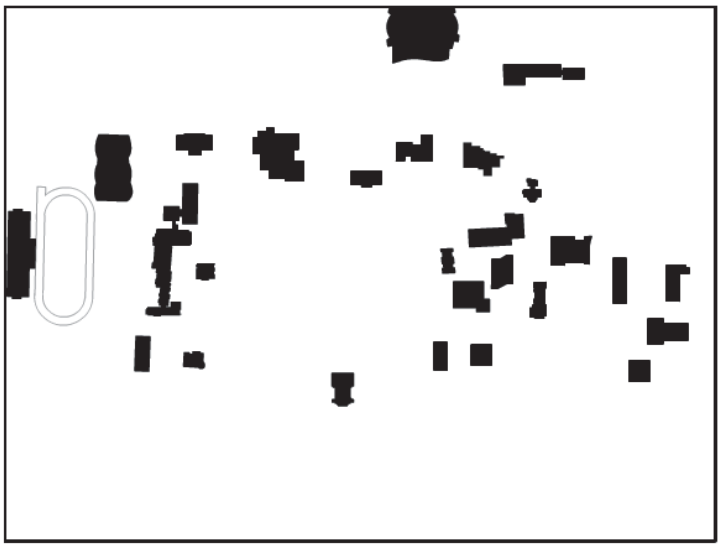

Fig. 5. One participant's map arrangement. Note the use of the rotation and alignment heuristics—the buildings have been arranged in orthogonal lines.

3.5 Space Syntax Analysis of the Campus

Space syntax measures of the test environment are needed to compare with the results from the spatial judgment and memory tasks. Figure 6 shows the axial map of the Carleton campus generated by the experimenter. The weight of each line represents the global integration of that axis—the thicker the line, the higher the global integration value. Each axis represents a straight line down a walkway.

3.6 Agreement Between Instruments and Space Syntax Analysis

Do these integration values from the space syntax analysis predict performance on the spatial judgment and memory tasks? In particular, I will consider the integration value of the axis leading to the main entrance of each building. When two or more axes converge at an entrance, I will use the higher integration value. Thus, performance on the pointing task can be compared against the integration values of the starting and ending buildings for each question, and similarly for any pair of buildings on the map arrangement task.

Mean error in degrees (aggregated across all participants) for each pointing question is significantly predicted by the global integration of the first of the pair of buildings (the given building as opposed to the destination building), β = -13.855, $t(10)$ = -2.435, p = .035, and accounts for a significant proportion of variance in mean error, R^2 = .372, $F(1, 11)$ = 5.930, p = .035. However, the global integration value of the destination building does not significantly predict

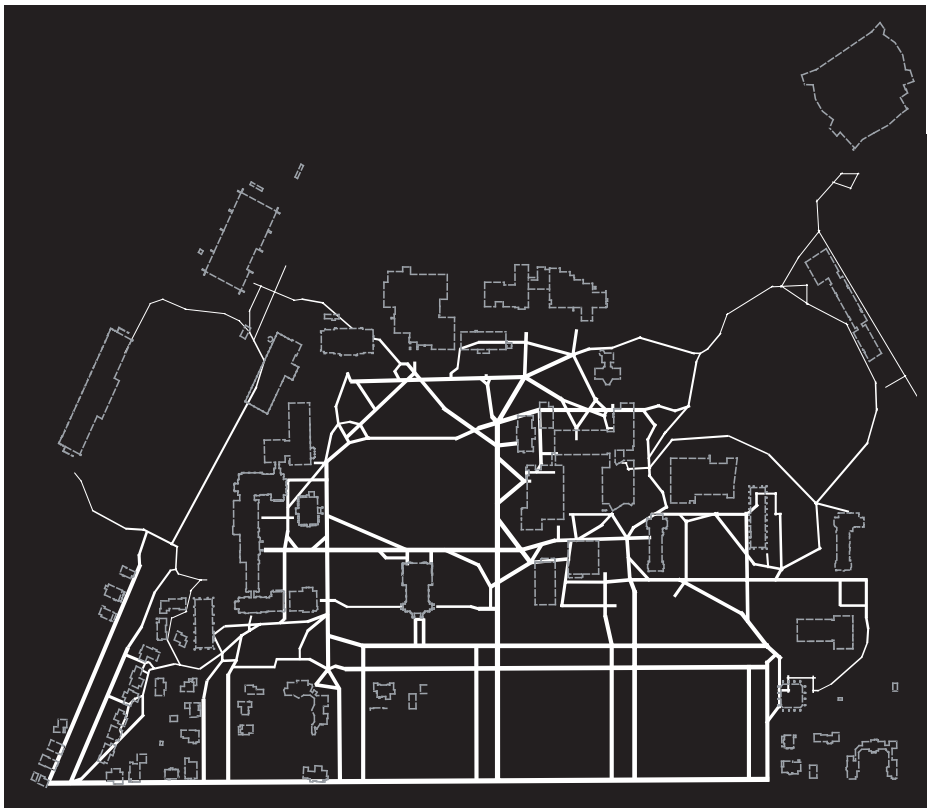

Fig. 6. On this map, axes represent pathways on the Carleton campus. Thicker lines indicate higher global integration values. Building outlines are indicated approximately with dashed lines. Note that the pathway locations came from a precise CAD plan, whereas the building outlines were added later from a less precise but more presentable map for the purposes of this figure.

the aggregate mean error in degrees, $\beta = 2.609$, $t(10) = 1.936$, $p = .710$. Put more simply, the global integration value of the starting building predicts participants' performance on a given pointing question, but the global integration value of the destination building does not have similar predictive power.

Local integration of the starting building does not significantly predict the aggregate mean error in degrees, β = -2.407, $t(10) = 2.180$, $p = .531$, suggesting that only global integration values have bearing on spatial judgment and memory tasks, and thus on our spatial knowledge.

The global integration value of the starting building significantly predicts the mean error in degrees on the angles between the same 12 building pairs as they were arranged in the map arrangement task, β = -12.046, $t(10)$ = -2.718, p = .022, and accounts for a significant proportion of variance in mean error, R^2 = .425, $F(1, 11) = 7.386$, $p = .022$. Again, mean error is not significantly predicted by the global integration value of the destination building, β = -1.301, $t(10)$ = -.233, p = .820. In other words, the global integration value of the starting building again predicts participants' performance on the map arrangement task, at least with respect to the 12 building pairs considered in the pointing questions.

For the 12 original building pairs considered, the global integration value associated with the starting building's entrance significantly predicts participants' error in determining the angle from that location to another building. This is true whether participants are considering that angle in the pointing task by rotating the pointer dot or in the map arrangement task by placing cutout pieces. The higher the starting building's global integration value, the smaller the mean error made by participants.

4 Discussion

4.1 Are the Same Processes at Work?

Are the same processes at work when a person makes angle judgments in the pointing task as when they choose where to place cutout pieces in the map arrangement task? Each participant's performance on the pointing questions correlated highly (r = .492) with their performance on the map arrangement. Yet participants' MRT scores only predicted their performance on the map arrangement but not on the pointing questions. These results appear at odds with one another, the first finding suggesting a strong connection between the instruments, while the second suggesting that only the map arrangement task relies closely on mental rotation. First, it must be noted that the correlation between the instruments is not large enough to control all variation in performance—these two findings may not be in disagreement.

My previous work (Dara-Abrams, 2004) suggests that the two instruments are actually different in nature. In that study, participants completed the Santa Barbara Sense of Direction Scale (Hegarty et al., 2002), which asks them to rate their confidence and ability at reading maps and navigating real-world environments. Participants' scores on that questionnaire correlated highly (r = -0.54)

with their pointing performance but not their map arrangement performance. Apparently pointing performance is more closely connected with one's real-world wayfinding abilities, while map arrangement performance is more directly associated with one's mental rotation abilities.

Consider the differences between the two tasks. On the pointing task, participants must imagine where the destination building stands in relation to the pointer dot, much as while navigating through an environment, we must imagine where our out-of-sight destination lies. On the map arrangement task, participants can see all the buildings on campus as they move one around the screen, much as how we evaluate one object rotating in relate to its surroundings. These are abilities measured by the Santa Barbara Sense of Direction Scale and the MRT, respectively. Thus, the findings of this study demonstrate that wayfinding abilities and mental rotation abilities are intimately connected—performance on the two tasks is highly correlated—but that these abilities are best measured by two different tests. Hegarty et al. (2006) find a similar partial dissociation between large, environmental scale spatial tasks (e.g., wayfinding) and small, figural scale spatial tasks (e.g., mental rotation).

4.2 The Form of Spatial Knowledge

Whether or not the two tasks make use of the same set of processes, they both call on the same set of spatial knowledge. Tversky (1981, 1992) has already demonstrated that this spatial knowledge is shaped by the alignment and rotation heuristics, and this study's findings only support that conclusion. What this study can contribute is evidence of how that systematically distorted spatial knowledge is shaped by the configuration of the environment in question.

It is the integration value associated with the starting building that predicts participants' performance on the spatial judgment and memory tasks, suggesting that participants' spatial knowledge of the place in which they are asked to imagine themselves is the key determiner of their performance. The format of the pointing task, with the simple line drawings from a bird's-eye view of the starting location, certainly suggests that they must use their prior spatial knowledge to associate that abstraction with an actual location. On the other hand, participants' spatial knowledge of the place they are asked to imagine pointing toward does not significantly affect their performance. This evidence implies that people only consider the local properties of the starting building when making such judgments.

However, recall that global integration but not local integration is strongly predictive. Since global integration measures interconnectedness with the entire axial map, the global integration value associated with the starting building will take into account the entire configuration of the test environment. Correspondingly, people may be considering the entire test environment when performing spatial judgment and memory tasks. While people may be consciously considering the global form of the environment in order to determine their responses, this evidence suggests that their spatial knowledge itself may be global in form. Peo-

ple's spatial knowledge may be structured as a comprehensive unit as opposed to being structured as a set of discrete, localized chunks.

4.3 This Particular Case Study

Properties of this particular test environment have certainly shaped the findings of this study, including the implication that spatial knowledge may be global in form. The Carleton campus is a discrete region with boundaries marked by physical features like streets, changes in building height, woods, and a river. Since the campus physically stands on its own, it would make sense for participants to know the campus as a unit. Therefore we would not want to conclude that all spatial knowledge is global in form—going against existing evidence for the hierarchical organization of spatial knowledge (for instance, Hirtle and Jonides, 1985)—based only on this study of one discrete region.

An unfortunate property of using the Carleton campus as a case study is that many of the building pairs that appear to be affected by systematic distortions include one building in the central (orthogonal) area of campus (e.g., the Language and Dining Center) and one building on the periphery of the campus (e.g., the Recreation Center), where the buildings are oddly-angled and are not arranged orthogonally. Those buildings that are on the periphery will most likely have lower global integration values. Is this due to the fact that they are on the periphery, and thus less centrally located, or are the low global integration values instead an effect of those buildings' odd angles and non-orthogonal arrangement?

Also worth considering is the axial map. The axial map used in this study limits the sightlines to pathways. Yet people clearly traverse other routes as they move around the campus. Moreover, they can see across open quadrangles, lawns, and roadways, none of which are considered with this axial map. An axial map that considers all spaces accessible to pedestrians (in ideal weather, presumably) might lead to different integration values for buildings. For example, redrawing the axes to allow for people walking across the Bald Spot, a lawn at the center of campus, would restructure the routes among all of the buildings fronting that region, and by extension, the global integration values for all buildings would be affected.

Axial map techniques were originally designed for analyzing dense urban areas with well-defined streets edged by solid lines of buildings. Obviously the Carleton campus, with its loose spacing of buildings and open quadrangles is quite different in its form. Other space syntax techniques, especially those designed for measuring visibility in open areas of building interiors, may be better suited for analyzing spaces like the Carleton campus. (See Dara-Abrams [2006] for my recent discussion of how to use space syntax techniques to model these types of environments.)

4.4 Spatial Knowledge and Integration

Why do participants remember the highly integrated locations more accurately than they do the less highly integrated locations? The more highly integrated a location is, the easier it is to access from elsewhere in the environment. This likely means that people travel more often through those locations, which are points along numerous paths. Prior research (as cited by Bafna, 2003) has found that the more highly integrated a location, the more pedestrians that are likely to be found there. That evidence reflects the aggregated behavior of many people, rather than the travel behavior of individuals, yet still supports the notion that more highly integrated locations are, on average, visited more frequently. This increased exposure presumably leads to richer spatial knowledge. In effect, a space syntax model can then be used to predict how well people are experienced with locations.

The link between spatial knowledge and integration may be more profound, as others have suggested. The network structure of an axial map may reflect the schematized nature of spatial knowledge. In that case, integration predicts the prominence of locations in one's cognitive map. Kim and Penn's (2004) finding that people's sketch maps accurately reflect the integration of streets in a neighborhood similarly suggests that axial maps parallel cognitive maps (although with sketch maps it is always unclear how the results are shaped by the constraints of the readout process). This study cannot definitively say whether integration simply predicts travel behavior and experience with locations or whether it also latches on to the deeper structure of spatial knowledge itself. Nevertheless, the results discussed here do indicate that computational models, such as axial maps, capture enough of the salient properties of space in order to account for a significant percentage of variance in performance on tasks of spatial judgment and memory. Put more simply, a formal description of an environment can be used to predict which locations in that environment will be more accurately schematized and and better remembered than others.

4.5 A Connection Between Cognitive Science and Urban Design

This study bridges two very distinct disciplinary worlds, that of cognitive science and cognitive psychology on the one hand and of architecture and urban design on the other. Whereas the former is concerned with producing a theoretical and empirical account of the human mind and similar agents, the latter focuses on the design and analysis of physical places. With this study I have attempted to empirically connect the two areas of research. With respect to cognitive science and cognitive psychology, these results provide real-world evidence of the rotation and alignment heuristics, while suggesting how our spatial knowledge relates to the urban form of an environment. At the same time, the results of this study lend support to the tools of space syntax, implying that they accurately describe properties of environments that we encode into our spatial knowledge. Thus, these tools have psychological meaning and can assess the human use and knowledge of environments. In architecture and urban design, fields in which

aesthetics are all too often the only consideration, space syntax measures could provide a useful method for also taking into account how humans actually perceive and use their surroundings. The world of cognitive science and cognitive psychology and the world of architecture and urban design may be of use to each other.

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Perception of Architectural and Urban Scale in an Immersive Virtual Environment

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Abstract. This paper presents a qualitative study of perception of scale. The study took place in an immersive virtual environment. The participants were asked to navigate in six virtual urban environments which had the same configuration but different properties of scale or proportion. The participants had to fill in a questionnaire of which the analysis is presented in this paper. Through this study a main hypothesis for the perception of scale has been created. This is that the perception of form affects the perception of both geometrical and topological properties of space. A new definition of scale is introduced which is the relation of form to space. This study brings up also the issue of the dualism of form and space in the existing literature and how this dualism can be overcome with the study of scale.

Key words: scale; perception; space syntax; virtual environment; navigation

1 The Problem of Scale in Architectural and Urban Theory

Scale has always been an important issue in architecture. It has puzzled both practitioners and theoreticians as questions about form properties of buildings, the relation of part to whole, the proportions of forms and the size and proportion of open-public spaces. The most common approaches on scale in architecture were normative indicating norms like “human scale” or “in context” as appropriate, or talking about “in or out of scale”, “harmonious scale” or “order”. Another use of scale focussed on the semantic/symbolic aspect when it was used to impress or to impose in authoritarian or monumental architecture. There is not extended literature on architectural or urban scale in architecture or in cognitive studies and studies of perception. Usually there is literature on perception of size, perception of distance, and perception of form but not of scale. In architectural studies usually it is referred to as architectural or urban scale but there is no actual word explaining the more complex relation of what a human mind perceives when walking down a street which is a combination of architectural forms juxtaposed in a specific formal configuration which creates the urban form. In a way, the wrong assumption is that the sum of the parts (architectural forms) is equal to the whole when what actually happens is that

the whole (urban form) is much more than the sum of the parts. We could call such a type of scale “cityscape scale”.

Relating the perception of scale to architecture, the interest would be especially with scale as an under studied issue in the syntactic theory first developed by Hillier and his colleagues in University College London. Space Syntax research has shown that human understanding of the built environment is closely related to the configuration of space as this emerges in two dimensions. It has also shown that the perception of space related to movement decisions can be mapped by a representation called axial line [4]. However, since forms are creating the configuration of space and forms have three dimensions this paper seeks to ask whether this third dimension is actually affecting the understanding of the built environment.

Therefore, the main question that this paper will try to investigate is how are differences in scale of an urban built environment perceived by people moving in it? There are two main points of this research. First is that the interest is on the perception of a moving and not static observer. Second, that the issue under examination is not the perception of distance or building heights or other metric properties of forms or space, but the interrelation of all these and how changes in one metric property of the built environment may affect the perception of another metric property.

Investigating the question of the perception of scale is a step forward into trying to understand whether the way people perceive scale has something to do with decisions they make about the use of space. Is the scale of the built environment an element of its configuration and as such does it affect people’s movement in cities? Or does the scale of the built environment affects the intelligibility of cities?

A clear distinction should be made here between the term “scale” as this appears in the Geography literature [11] [15] [19] [24] and the “scale” this paper is dealing with. Scale in geographical studies is an abstract notion referring to the extent, either spatial or temporal, to which a phenomenon, physical or not, applies. In the geography studies there is no reference to architectural and urban scale as this is defined in this paper, as the scale of the forms in relation to space. This is a more concrete sense of scale dealing with the relation of form to space which is apprehended through movement.

The methodology used to investigate the issue is that of an experiment of navigation in a virtual environment. The experiment is presented in the third section of this paper. In the next section, some key theoretical concepts related to the problem of scale are presented which are necessary to understand the set up of the experiment.

2 The Dualism of Space and Form in the Existing Literature and the Perception of Scale

Most writers coincide that scale is the relation of something to: either a standard (meter, foot, tatami, Modulor [8] [9] etc.) in which case is an external relation, or to the human body (Plato, Vitruvius, DaVinci, Modulor, foot) in which case is an internal relation, or of things among themselves (Pythagoreans, Golden section, Fibonacci series etc.) which usually appear with mathematical relations. Therefore the

question of scale brings back the philosophical question of relations in general and specifically the relation of parts to a whole.

Scale can be found in the literature as the issue of proportion [1][12][20][22][29][33] or proportion systems [8][9][27]. It is sometimes defined as relative size [10][16], sometimes referred to with its symbolic use [17][28][34]. Scale also appears in the literature in the discussion on context [3][18] or contextual architecture [30]. There have also been attempts to quantify scale as a property of form [7][14][23] and quantification of scale as a property of space [25][26]. The issue also of hierarchical scaling and how this is helping human understanding of the built environment is quite interesting [13].

All of the above studies of form and space have taken place independently and there is no study examining how the perception of form affects the perception of space and vice versa. What all these studies are missing is what happens when forms are put together to create an urban environment. This is the main concept that this paper will try to take forward. How do the different forms relate to each other and even more how do they relate to the space that is created by the arrangement of these forms? Accepting that there is a dualism of form and space in the existing literature, this paper will introduce scale as the connector of the two. It suggests a definition of scale which brings architectural, urban and spatial scale together. The definition of scale that this paper is presenting is this complex set of relations that take place in the urban arrangement of architectural forms and the relation to the space that these forms create. Then we can ask the next question which is if actually there can be such a thing as perception of scale.

If scale is a complex set of relations as has been defined above, a justifiable question would be if the human mind can actually perceive these relations or if it is storing the information it gets from the environment into relational coding. So actually can we talk about perception of relations or the information acquired through perception is interpreted into relations in human mind through a cognitive process? In other words, is it our mind that interprets the information into relations or configurations or do we perceive them as such? The following experiment has been designed in order to examine questions like these. It is an attempt to understand how scale is perceived by people navigating in an urban environment.

3 Description of an Immersive Virtual Environment Experiment

The reason that this experiment was conducted in a virtual environment was because it's hard to separate scale as an independent variable in a real environment. In the specific research, the variable is scale as a factor of the built environment. In a virtual environment experiment the researcher can manipulate independent variables and the perception of each variable in a more controlled way than in the real environment.

Any virtual environment experiment brings up the problem of relevance of a real to virtual environment. Previous research investigating topological perception and wayfinding, in real and virtual environments [2] has shown that movement patterns in real and virtual environments are very much alike, letting us conclude as a result, that knowing the movement pattern in a virtual environment can lead to a prediction of the

movement pattern in the same real environment. Research on the perception of metric properties of space, like distance, on virtual and real environments has shown that distances are not perceived the same in a real and in a virtual environment [31] [32]. This may have an effect in experiments related to scale taking place in virtual environments. In the experiment presented in this paper the relevance to a real environment is not under investigation. The question is how the perception of distance for a moving observer in a virtual environment differs according to the heights and size of the forms along this street. This differs from research on the perception of distance in an urban environment since what is examined is not perception of distance per se but how this is affected by perception of sizes and scale of forms.

The experiment presented was a pilot study. The objective of this virtual experiment was to examine if and how differences in scale and proportions of the built environment are perceived. The constant of the environments was, in syntactic terms, the configuration of space which has been proved by space syntax [5] to be the main property of space of the built environment which people perceive and base their moving action on. In other words, the configuration of space is how space is cognised and the main factor that affects perception and decision making related to movement and navigation.

The present experiment considers the configuration of space as being the invariant in six different environments and scale and proportions being the variant. Knowing that people's perception of these environments is not affected by differences in the configuration, we can test the effect of scale on perception. However, since scale is not one specific property but depends on various relations among elements, different environments had to be recreated with each one approaching and examining a different kind of relation. So for example, in one case the forms have changed, the variant was the height of the buildings, in another the scale of the environment in relation to the observer, and in another the relation of parts to whole of the built environment by introducing hierarchical scaling (pavements, windows and doors).

3.1 The Experiment

3.1.1 Description of the Method of Navigation in an Immersive Virtual Environment

The software used for the navigation in the virtual environment is called Candle (initially authored by Nick Dalton and next version by Chiron Mottram) and was developed in University College London. The head mounted display system used for the experiment is called Arthur AR Prototype Display system or AddVisor™ 150. This is a helmet like apparatus with two miniature flat panel displays. The displays are full colour 1280*1024 pixel computer screens, one in front of each eye and each giving a slightly different view so as to mimic stereoscopic vision. The horizontal field of view is 54 degrees horizontal by 29 degrees vertical. The tracking system used was Motion Tracking by Ascension with an Inertia Cube by Intersense. The position and orientation measurement system was called The Flock of Birds.

The models were drawn in two dimensions first in "Autocad 2005, Autodesk" and then the three dimensional models in "3d Studio Max v.7, Autodesk". The extracted data, which were the position of the object in the virtual world and the direction of the

head, were saved twenty times per second as an ASCII text log file. These data files were then imported in Mapinfo Professional v7.5 in order to visualise and manipulate the data.

3.1.2 Description of the Worlds (Virtual Environments)

The experiment consists of two groups of six virtual environments each. Both groups are based on two small urban layouts presented by Bill Hillier in the book "Space is the Machine" [6]. These two urban layouts are constituted by the same number and size of blocks but one layout is more intelligible than the other. Intelligibility is a syntactic measure [6] which shows the relation between local and global structure in a system. Space Syntax research has shown that an intelligible system is easier to navigate than a non intelligible one. The difference in intelligibility in the experiment's environments is achieved just by a slight movement of the blocks. However, the layouts used for the virtual environments were not exactly the same as the original ones but slightly modified. While in "Space is the Machine" all the side edges of the layouts were flat walls, in the current experiment the edges have been treated in the same way as the rest of the environment with the creation of extra blocks leading to dead-ends. This modification was done in order to make the world look more realistic. Figure 1 shows the original and the modified worlds. The reason that an intelligible and a non-intelligible world were used was to examine if differences in intelligibility would have an effect on the perception of scale and vice versa, if the scale differences would change the perceived intelligibility of space.

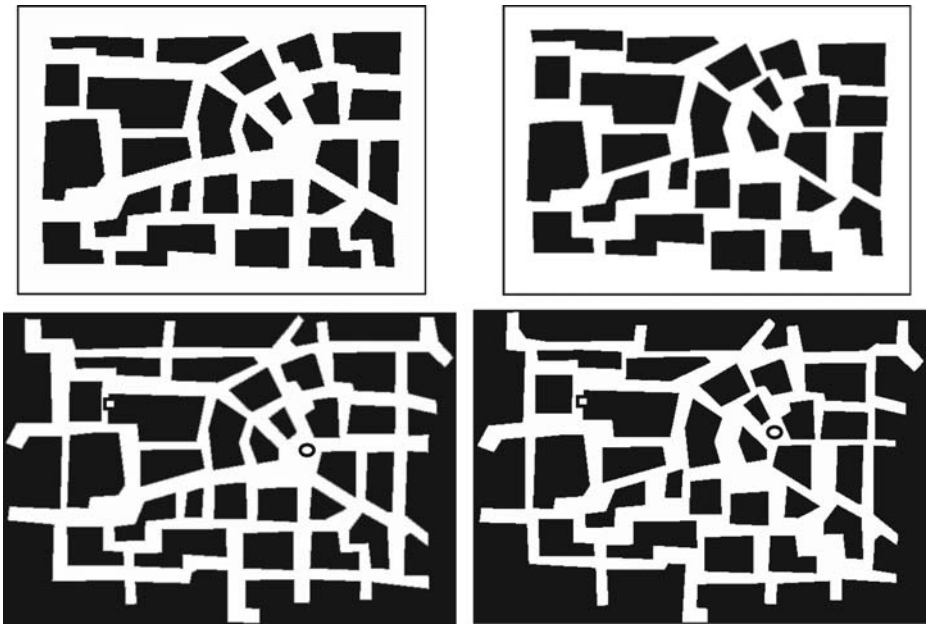

Figure 1 The original layouts (top), as presented in Space is the Machine, and the modified layouts (bottom) used for the virtual experiment. The small white square on the left side of each

world shows the location of the object the participants had to find and the dot on the right side the starting point.

Two groups, one based on the intelligible layout and one on the non-intelligible, were created. The differences among the six environments were related to the scale, proportions and building heights. The diagram in Figure 2 sketches out the differences among the six environments. The code names were A1, B1, C1, D1, E1 and F1 for the intelligible worlds and A2, B2, C2, D2, E2 and F2 for the non-intelligible worlds.
In worlds A1 and A2, all the buildings had the same height which was 6 meters. There were no doors or windows on the buildings. In worlds B1 and B2, the buildings had different heights and these were 3, 6, 9, 12, an 18 meters. The height of each building was randomly chosen. Again, these worlds had no doors or windows.
The previous worlds were designed to test:

- how environments with same configuration but different heights, and therefore different proportions, would be perceived
- if the differences in heights of buildings would play a role in enabling or disabling navigation and wayfinding

In worlds C1 and C2, everything was double size of worlds A1 and A2. As a result, all the buildings had the same height which was 12 meters. Width and length of roads were double than in worlds A1 and A2. Worlds D1 and D2 were double scale of worlds B1 and B2 respectively. Therefore, the heights of the buildings were 6, 12, 18, 24 and 36 meters. None of the worlds C1, C2, D1, D2 had windows or doors.
Pairs of worlds C and D were designed to test two questions. First, by comparing results of worlds A and C and B and D, the question tested would be:

- how environments with same configuration and same proportions but different scale related to the human body as the standard (longer and wider streets and higher buildings in C and D would be perceived
- whether the differences would affect navigation and wayfinding

Second, in relation to each other, C to D, will be compared to the results from A and B, and the question tested would be:

- whether the differences in proportions (from C to D and from A to B) are perceived in the same way in different scales environments (C,D to A,B).

Finally, worlds E1, E2, F1 and F2 were exactly the same as worlds A1, A2, B1 and B2 with extra feature that they had windows and doors and had pavements. So actually, E1 and E2 had same height buildings and F1 and F2 had different heights. The doors, windows and pavements were designed to introduce hierarchical scaling as they were giving a sense of familiar size, doors, windows and pavements, to compare to the buildings size. In all cases, the ground floor was constituted with doors and big windows (like shop windows) and all the floors above with sliding windows. Each floor was considered to be 3 meters high which resulted to have 1 floor buildings (3meters), 2floors (6meters), 3floors (12 meters) and so on.
The worlds E and F, in relation to A and B, were designed to test:

- how environments with the same configuration, same proportions in the sense of same heights but different proportions in the sense of constitution with windows and doors or scaling hierarchy, would be perceived
- whether the differences would affect navigation and wayfinding

The size of each of the small worlds was around 260mx400m and the big 520mx800m. The participants were starting from the same point in all environments, which was in the centre of the small square, and it is indicated with a white dot on the modified plans of figure 1. The height of eyes of each participant was constant at 1.70m. The speed was always the same and approximated with normal walking speed at 7km/h. The task was to find an object on one of the buildings and if found to go back to where they started. The object is indicated in figure 1. The object was at the same place in all worlds and the location was chosen after the spatial analysis showed the specific space to be one of the more segregated. The participants had ten minutes to complete the task. The collected data were the x, y, z coordinates of the position of the participant and the direction of the head. The data was collected 20 times per second. These data give the route of each participant in each world. All the routes will be studied in order to find whether patterns emerge. Questionnaires data were also collected which are presented in the next section.

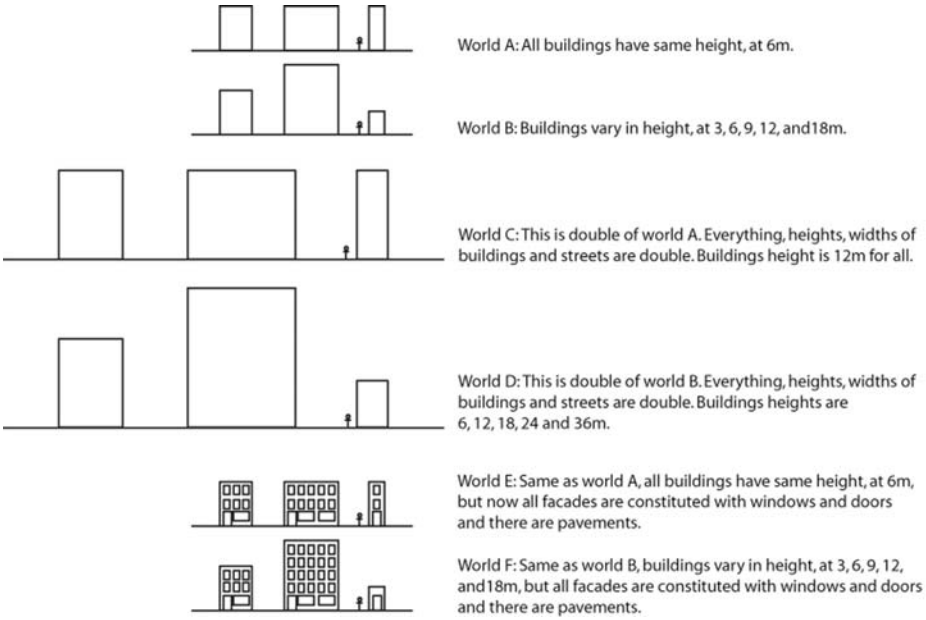

Figure 2 Sketch diagram of each of the six worlds.

3.1.3 Questionnaire

The routes of the participants are expected to give information about the perception of space on a non-conscious level. In order to capture a more conscious side of perception, the participants were asked to reply to questions related to the differences between the worlds. The questionnaire consisted of two parts. In the first part there were questions on personal data like sex, age, occupation, previous experience in immersive environments and previous experience in non-immersive environments like computer games.

The second part of the questionnaire consisted of questions related to the experiment. The first question of the second part asked whether the participants had noticed any difference between worlds A and B (A1 and B1 or A2 and B2 depending in which group the participant was).The second question was about the differences among the four worlds A, B, C and D (again A1, B1, C1 and D1 or A2, B2, C2 and D2 depending on which group the participant was). The third question asked the participants whether they had found any of the six environments easier to navigate and to explain why. The purpose of this question was to identify how the participants had perceived the intelligibility of the environments in a conscious level. The final question asked the level of difficulty in moving around in the virtual environment. If they found a difficulty they were asked to explain what it was. The purpose of this question was mainly to identify cases in which the difficulty in navigation was not due to the properties of the environment but due to the nature of the experiment being virtual and problems related to the apparatus.

3.1.4 Participants

The participants in the experiment were twenty two unpaid volunteers. Eleven of them participated in the experiment with the group of intelligible worlds (A1, B1, C1, D1, E1, F1) and the other eleven in the group with the non-intelligible worlds (A2, B2, C2, D2, E2, F2). The participants' occupation was representing a bias towards researchers and architects. Table1 shows the statistics for each group.

Table 1 Details of the participants in the experiment.

	Group 1		Group 2
Sex	55% female		45% female
Age	55% 30-35yrs old	27% 25-30yrs old	73% 25-30yrs old
Occupation	91% researchers		60% researchers
Architects	45.5%		64%

3.1.5 Experiment Procedure

The participants had in the beginning a test navigation to get used to the apparatus and then had 10 minutes for each experiment. The questions were answered some during and some after the experiment. In order to avoid any bias related to the order of the worlds, the order was different for each participant but organised in such a way to allow the question to be answered.

4 Hypotheses Deriving from the Virtual Environments Experiment

The findings presented in this paper are based only on the analysis of the questionnaires and on the anecdotal comments the participants were making during the participation in the experiment.

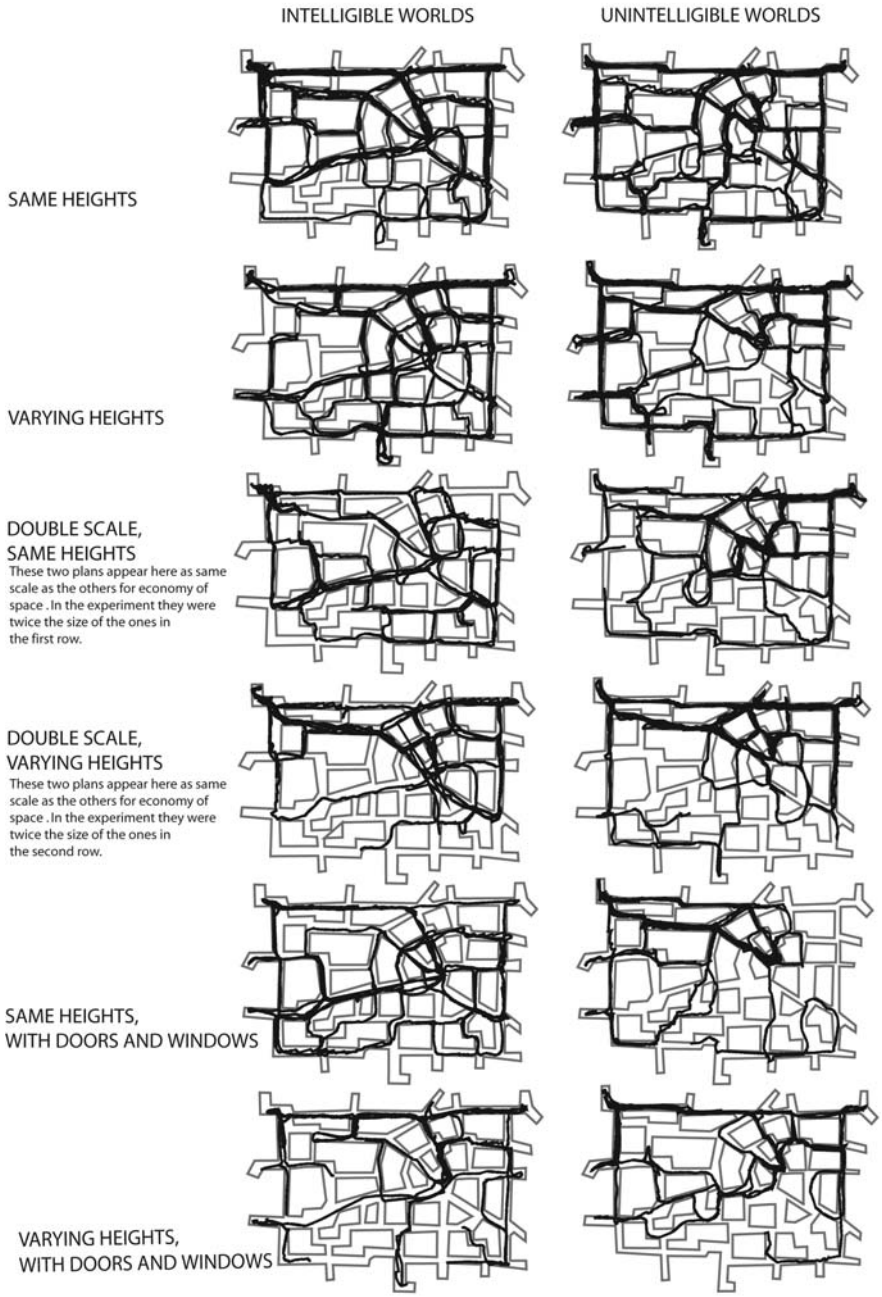

Figure 3 The traces of the participants in each of the 12 worlds.

A basic hypothesis deriving from the study is that changes of forms can affect the perception of both geometrical and topological properties of space. Geometrical properties of space are so related to the forms creating this space that we cannot actually isolate the study of geometrical attributes of space from the study of forms. For example, it seems that the perception of the length of a road is strongly related to the heights of the buildings along this road, or to the distance of the buildings etc. Therefore the study of geometric properties of space should be reduced to the study of scale of the environment as this is defined in this paper; this is the relation of form to space.

Figure 4, on the top row, demonstrates three snapshots each one taken in a different virtual environment. The snapshots are taken from the same point and towards the same direction in all three environments. The difference in the perception of the length of the road in each case can be noticed. The second row illustrates another two snapshots of the same street, one in environment with same heights and one in environment with different heights. The fact that the length of the street is perceived as being different in each case though it is the same, can be paralleled to the Muller-Lyer illusion, also illustrated in Figure 4.

As for the topological properties, it seems that they are not perceived as the same when the geometrical properties of the environments are not the same. The six environments had the same exactly topological properties and they were not perceived as such. It has been argued in the space syntax literature that the axial line is an allocentric property of space [21] and therefore independent of the subject, but at the same time it represents what the human mind perceives of space, and since human mind is embodied therefore the axial line is embodied. Based on the findings of this experiment, this paper puts forward the hypothesis that scale is mediated between the allocentric representation and its embodiment. In other words, the environments have all the same allocentric property (same configuration) but depending on scale they are embodied in different ways. This means that the way the axial line becomes embodied depends on scale. So, although the axial line, as a spatial representation, is still there and is still perceived as an axial line, some of its attributes may be affected by the scale of the environment. The axial line keeps its attributes and its topology but it now has extra information added to it which affects the decision of staying or not on the axial line; it affects the reading by the observer of the environment or in other words, the way the intelligibility of space is perceived.

The patterns of movement in each world appear in figure 3. A common method in space syntax studies for correlation of number of pedestrians to axial values was used [5]. Virtual lines or gates were put across the width of every street of the model. Then the number of pedestrians/participants crossing this virtual gate is plotted in a graph against the value of the integration of the axial line crossing the same gate. In the experiment presented in this paper, the relation between the number of participants counted at a gate and the integration value of the axial line crossing this gate, as measured by the correlation coefficient of the graph, is very weak and therefore

cannot be considered statistically proved[1]. However, it seems that the environments with the same heights appear to have a stronger correlation than the ones with varying heights in both intelligible and non intelligible environments. The only exception to this is the intelligible double scale worlds (C and D) which have about the same correlation coefficient.

However, in any case, the different heights and scale affect the perception of the environments in different aspects. The way it affects the perception of the environments will be presented next.

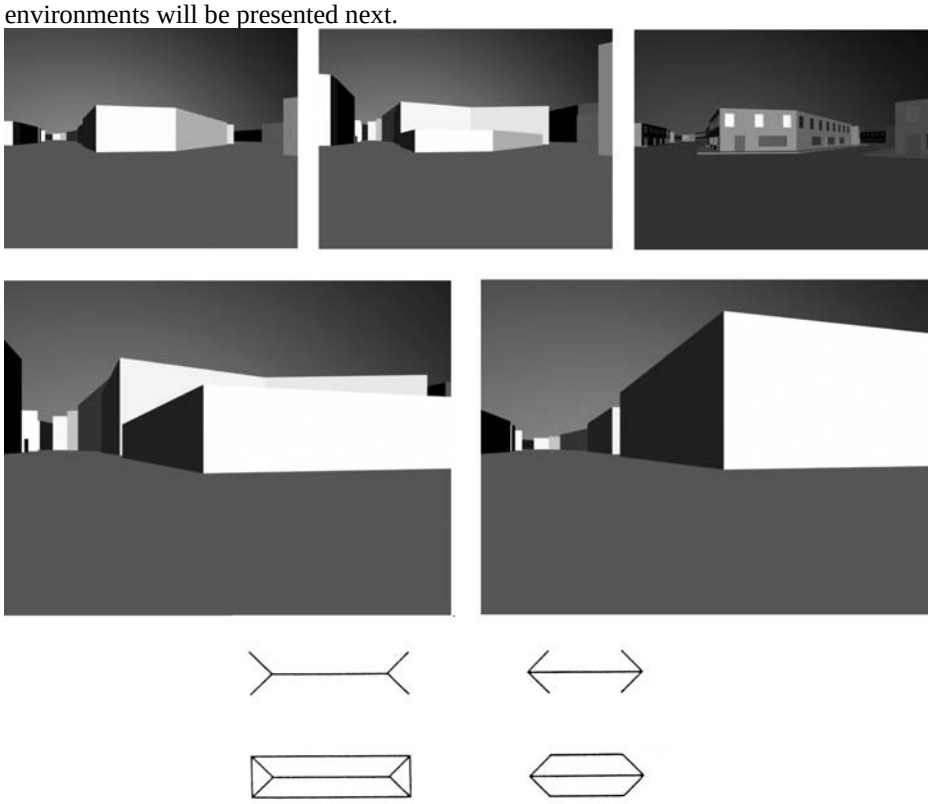

Figure 4 Top row, three views of the same street with different forms on each side. Middle row, two views of another street with different forms on each side and at the bottom the Mueller-Lyer illusion.

[1] The table presents the correlation coefficient between number of pedestrians/participants and integration value of the axial line for each world.

	World A	World B	World C	World D	World E	World F
Intelligible	0.20	0.16	0.10	0.11	0.17	0.10
Non Intelligible	0.10	0.01	0.13	0.10	0.31	0.01

The differences in perception can be identified in seven thematic groups; sense of distance and geometric properties of space, sense of order and structure, sense of similarity, sense of scale, sense of hierarchical scaling, recognition of landmarks and movement and navigation. For further research, each one of these differences can be tested on its own and more thoroughly. Based on the replies of the questionnaire the results of questions A and B are presented in Table 2, Table 3 and Table 4.

Sense of distance and geometric properties of streets. The streets in same height environments were perceived as longer or wider than in the different height ones. However, this difference does not apply in the big scale environments as it will be presented later. Participants' comments were:

> "there was a distinctive broad alley" (mentioned by a participant as difference between A1 and B1, however the width was the same in both cases).
>
> "there were more narrow paths (in B1)"

This refers back to the Muller-Llyer illusion, with its relevance in architecture (Figure 4). However, it is interesting that many participants mentioned that in different height environments they found the roads longer than they expected. This means a difference between perceived and traversed distance i.e, that the expectation of a road looking short due to buildings with different heights was not met when the participant started actually walking along this road and therefore the road eventually felt longer.

Another case was the recognition of wider streets in environment with same heights.

> "wider streets (in A1 than B1) made it sometimes easier to make your decision where to go and to navigate"

Sense of order and structure. The environments with different building height were perceived as less ordered than the ones with the same.

Participants' comments were:

> "the one with different heights was more confusing"
>
> "the street network structure seemed different, the first (the participant means A1 with same heights) was more regular and the second (the participant means B1,different heights) more irregular"
>
> "last one (B1) had lots of irregular spaces"

Also, differences in angles (between A1 and B1) were found.

> "the streets were more angular (in E2 than in F2)

Sense of similarity. In the few cases that the environments were identified by the participants as the same were only when the buildings heights were the same. The same height was enabling the recognition of the configuration as the same. Furthermore, in the cases of same height buildings that the environments were identified as the same, the participants had learned their way to the target. They were using the same route in all experiments to find the door and then go back to the starting point. Participants' comments were:

> "the second and fourth (A2 and C2) were exactly the same. The first and third (B2 and D2) could also be identical but it was too hard to tell"
>
> "the 1st, 3rd, and 5th (B1,D1 and E1) were more or less indistinguishable in terms of visual qualities" (we must remark that this participant didn't identify any differences related to the forms, like different heights or double scale)

In one case that the environments A, C and E were identified as the same, it was due to a wide alley. Of course this wide alley had the same width in environments A and E and was wider in C. Even more, the alley had the same width in environments B and F as in A and E but was not recognised as such due to the varying building heights. Similarly, the width in environment C was the same as in D but again was not recognised as such. What was identified in all cases as the same was the existence of an alley which seemed to be wider than others in the environment.

Sense of scale. The bigger scale (double) was mainly not recognized as such. The suggestion is that this is related with the virtual character of the experiment and the issue of embodiment. It will not be expected in real world a double difference in scale not to be recognized as such (at least bigger if not double). In this case the non embodiment of virtual environments can be questioned. Possibly because of the non direct participation of the body the change in scale is not perceived.

The differences mentioned above, of geometrical properties and of order, were only perceived as such in the small scale environments and not in the big ones. A reason for this could be that in the big environments these differences were actually taking place out of the close visual field of the participant and therefore were not strongly perceived.

Sense of hierarchical scaling. It is not clear if the hierarchical scaling with the existence of pavements, doors and windows was helpful or not. It was helpful for some participants and confusing for others. Some of their comments were:

> "too much detail",
> "too cluttered with windows etc."
> "windows and doors didn't make any difference"
> "the fifth one (F2) was easier with pavements, doors and windows with colors and varying building heights"
> "the last two (E2 and F2) with doors, pavements and windows, seem to give more information about the form of the space"
> "the last two(F2 and E2) were probably easier because there were pseudo-real building elements rendered in the scene"

Table 2 The table shows the results of Questions A and B of the questionnaire. There were 11 participants in the intelligible and 11 in the non-intelligible environment.

	Question A: Similarity between environments A and B			Question B: Similarity between environments A,B,C and D		
	Intelligible (N=11)	Non-intelligible (N=11)	Total (N=22)	Intelligible (N=11)	Non-intelligible (N=11)	Total (N=22)
Exactly the same	0	2	2	0	0	0
Different but cannot tell/remember what	3	3	6	1	2	3
Different	7	6	13	8	9	17
other	1	0	0	2	0	2

Movement/ Navigation. In the bigger scale there was a perception of slower speed than that the streets were longer. Actually, the difference in the two environments was considered as slower speed of the apparatus. This wouldn't be expected to happen in a real environment but in a virtual environment it was perceived as such due to the lack of bodily effort.

Some participants thought that same height environments were easier to navigate. It is interesting that couple of them found this opposed to their expectancy. The same height environments made them feel that the visual field was wider. Possibly this was due to the fact that the same height buildings were quite low as well (6m). Some comments:

> "(E2) seemed easiest although there was little building height variation"
>
> "the very last one (E2) was easier, despite the wall height being constant, because there seemed to be more (longer) visibility available which somehow made it easier to navigate and remember the path"
>
> "the one with the low buildings was easier to navigate because you could see around better"

Table 3 The table shows the differences that participants who identified environments A and B as different, found (this is the third row of table 2; there were 13 participants who identified differences). Just to remind that there was no other difference than the building heights.

Differences recognized between A and B	Number of participants (out of 22 only13 identified differences)
Heights	11
Layout of two worlds	5
Shapes of the buildings and blocks	4
B more irregular and confusing than A	3
Streets were narrower in B	3

Table 4 The table shows the differences that participants, who identified environments A, B, C and D as different, found (this is the third row of table 2; there were 17 participants who identified differences).

Differences recognized between A, B, C and D	Number of participants (out of 22 only 17 identified differences)
Heights[2]	15
Streets and open spaces characteristics (length, width, bigger open space)	8
In size (or scale) just as bigger and not double size	6
Layout of the worlds	4
Shape difference	2

Another issue related to the low buildings which helped navigation was the view of the sky. Some participants thought that they were helped in navigation if they could see the sky.

> "too difficult to navigate because I could not see the sky always" (talking about the big scale environments)
>
> "higher walls in the 4th environment (D1) made it more difficult to navigate because I couldn't always see the sky"
>
> "the fifth one (E2) was the easier one, the walls were quite low, not so high, there was no other obstacle when one's viewing the sky, the streets were quite vast"

However, other participants found the differentiation in building heights interesting and helpful.

> "there was a lot of building height variation which at least made the journey more interesting"
>
> "certainly, the differentiation in the height of buildings was helpful in navigation"

[2] These participants mentioned as difference the heights of the buildings but they didn't necessarily grasped the correct relation of heights (double for example) among all four environments.

"environments with buildings of different size and streets of differing widths were easier because I could tell the difference between them – easier to orient myself"

"the last one is easier to navigate because it gives more information about where I stay in that environment such as the height of the building"

Recognition of landmarks. Areas with very low buildings (3m) were considered as "squares", like open spaces because they could actually see the buildings at the back. The participants were saying for example that:

"in worlds B and D there were more squares"

"low building in a square"

The worlds with squares were perceived as easier for navigation.

"…look in the distance above lower buildings to think where to go and where I had been"

5 Conclusions

This paper has explored the concept of scale in architectural and urban theory. The interest is specifically in the perception of scale, as this is perceived by pedestrians walking through cities.

In order to investigate the issue of the perception of scale, the method used was that of navigation in virtual urban environments. The environments had the same configuration but different properties of scale and proportions. The principle hypothesis deriving from this experiment is that the perception of form affects the perception of both geometrical and topological properties of space. Geometrical properties of space like length and width of roads were perceived as different depending on the heights of buildings being the same or not. Also, although the environments had the same configuration, therefore they were topologically the same, they were not perceived as such.

The paper also suggests that there is a kind of dualism between form and space in the existing literature. The relation of space and form has not been thoroughly studied and the paper suggests that this relation can be studied through the concept of scale. Scale is relations, it could be relations of forms or relations of space, but when studying an urban environment, scale is most of all the relations of the juxtaposed architectural forms to the space created by these forms. Therefore scale is defined as the relation between space and form.

The findings of the experiment also reinforce this hypothesis since they bring up a relation of the perception of space to the perception of form. Therefore a study of scale should not look into form and space independently from each other.

This paper sets and opens up many questions related to the issue of scale and suggests many issues for further research which was the point of conducting the pilot study in the first place. A main question which would have a direct implication on navigation in cities would be if actually the perception of scale, as this is defined in this paper, affects the perception of the intelligibility of cities, of the understanding of cities from human minds. A first clue from the findings of the experiment is that it does but it still needs further research.

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Lighting within the social dimension of space: A case study at the Royal Festival Hall, London

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Abstract. This paper investigates light within the social dimension of space and the influence that lighting may have on visitors' overt behaviour, therefore attempting a link between behavioural, qualitative and configurational issues of the built environment. Factors such as environmental or lighting conditions could affect the visitors' experience and formulate the communication between the visitor and the building. The aim is to investigate whether or not there is any correlation between patterns of space use and luminous patterns of the visual field, while providing an understanding of the relations between behavioural, subjective and visual reactions and on the aspects of the physical environment that cue them. In order to test the hypotheses an intervention study takes place at the Royal Festival Hall in London. The results argue that lighting does affect the local pattern of movement and interaction. However, one of the crucial factors of the actual interaction remains the identity of the presence of people in the area, which seems to overcome any configurational or other architectural attempt to intervene with the setting.

1. Introduction

This paper investigates light within the social dimension of space and the influence that lighting may have on visitors' overt behaviour, therefore attempting a link between behavioural, qualitative and configurational issues of the built environment. The hypothesis is that in every building there are qualitative aspects of the built environment apart from spatial configuration that play an important role in the experience of architecture. Factors such as environmental or lighting conditions could affect the visitors' experience and formulate the communication between the visitor and the building. The aim is to investigate whether or not there is any correlation between patterns of space use and luminous patterns of the visual field, while providing an understanding of the relations between behavioural, subjective and visual reactions and on the aspects of the physical environment that cue them. Lighting research on the behavioural effects of lighting supports the notion that lighting can be used to cue attention, orientation and wayfinding. Many of those studies have been concerned with metrics of lighting quality and the perception and less often the behavioural effect of the luminous environment on the occupants yet in this paper the direct link between qualitative and configurational issues is attempted with the use of space syntax analysis.

In order to test the hypotheses and study the effect of lighting on visitors' interaction within a setting, an intervention study takes place at the Royal Festival Hall in London, at a public area that works as an information spot. Photometric measurements are taken to represent and evaluate the existing conditions and a set of relighting experiments, altering the appearance of the space in terms of luminous pattern, light levels, distribution and light source colour, is applied. Observations of visitors' movement and interaction patterns take place before and after the interventions to monitor the response and affect on space use. Spatial analysis with space syntax tools is applied to study the configurational issues of the setting while the visual field luminous pattern is analysed in combination to the syntax of vistas in the space. The results argue that lighting does affect the local pattern of movement and interaction. However one of the major findings was that the crucial factor of the actual interaction was the identity of the presence of people in the area, which seems to overcome any configurational or other architectural attempt to intervene with the setting.

2. Lighting research

When analysing the effect that light has on people, most of the relevant literature in lighting research deals with subjective preferences, impressions and expressed opinions about the way we perceive space. The most representative part of this research was conducted by John Flynn during the seventies. His work concluded on a series of design recommendations that provide some basic guidelines on the impression of space.

Subjective Impression	**Reinforcing Lighting Modes**
Impression of Visual Clarity	Bright, uniform lighting mode Some peripheral emphasis, such as high reflectance walls or wall lighting
Impression of Spaciousness	Uniform, peripheral (wall) lighting Brightness is a reinforcing factor, but not a decisive one
Impression of Relaxation	Non-uniform lighting mode Peripheral (wall) emphasis, rather than overhead lighting
Impressions of Privacy or Intimacy	Non-uniform lighting mode Tendency toward low light intensities in the immediate locale of the user, with higher brightnesses remote from the user Peripheral (wall) emphasis is a reinforcing factor, but not a decisive one
Impressions of Pleasantness and preference	Non-uniform lighting mode Peripheral (wall) emphasis

Table 1. Lighting reinforcement of subjective effects. From Flynn, J. E. A study of subjective responses to low energy and non-uniform lighting systems. Lighting Design and Application. [15], February 6, 1977

The aforementioned work has been dealing with our perception, impression and evaluation of lighting. Yet in order to further comprehend the impact of the lit environment it would be crucial to consider the way the latter affects our overt behaviour as well. As studies [1] have shown, the links between expressed opinions and overt behaviour can be tenuous. Therefore, assumptions or forecasting of human behaviour cannot be substantially derived from the impression or evaluation research that focuses on the perception of the environment and not on the overt behaviour. In order to establish and quantify the extent to which lighting affects users, there have been studies that attempted to link certain lighting conditions to overt behaviour by observing the way people use space.

The results have showed that lighting can affect not only our perception of space but also the way we use space. It has been shown that people follow the direction of higher brightness around a barrier [2], supporting the notion that directing light in a space can aid circulation and wayfinding. Flynn and Subisak [3] while exploring the "moth effect" concept on overt behaviour and orientation suggested that a corollary of it applies to humans. They studied the sitting patterns in a restaurant setting, with adjustable high contrast lighting arrangement. In the first setting, people chose to sit away from the lit area yet facing it along with the centre of activity, the entry stairs. In the second setting, they still chose to stay away from the new lit area, yet still facing it but this time without facing the entry stairs as well. Their results on the patterns of seat selection argue that people gravitated towards the bright areas but rather than moving into them, chose to sit facing them, whichever the arrangement.

In a similar study, Yorks and Ginthner [4] found an affect of wall lighting on desk selection. Subjects were asked to enter a room, and sit at one of three desks located near the door, in the middle and at the far side of the room, to complete a paper task. Most subjects chose to sit to the desk located next to the door while when the wall was illuminated most subjects chose to cross the room and sit at the desk next to this wall. Taylor and Sucov [5] studied the effect of light on route selection processes. People were asked to chose one of the two paths available and proceed to a room in the back to complete a paper task. In the study, when the illumination of both paths was of equal level, 69% of the people went to the right. Whereas when the path to the left had a higher level of illumination, 75% of the people went to the left. The study concluded that people were attracted by higher illumination, following the brightest path.

In addition to these effects, lighting has been shown to affect other activities too that are not directly related with vision, for example raised levels of illumination have been linked to an increase in the sound or noise level. Sanders et al [6] studied the noise produced by groups of people talking while waiting in an assembly room. Low, uneven illuminance pattern was associated with less noise while a higher more even illuminance was associated with higher human noise and activity. Furthermore, research on the links between lighting and human performance has shown that higher illuminance can positively affect reaction times [7], brain activity and alertness [8].

Yet, most of the studies on the behavioural aspects of lighting have analysed a limited range of illuminance, had also the difficulties of minimising the effect of other factors on the recorded behaviour and should be interpreted with caution. However, they have shown that there is an often significant and measurable affect of lighting on behaviour. Lack of further research and more consistent findings has been one of the

reasons that our understanding of the relations between behavioural, subjective, and visual reactions, and which aspects of the physical environment cue them, still remains primitive.

3. Space Syntax

In an effort to spatially analyse the setting, space syntax methods were employed. Space Syntax is a theory along with a set of techniques aimed to analyse spatial configurations of all kinds, especially where spatial configuration seems to be a significant aspect of human affairs, as it is in buildings and cities [9]. Conceived and developed since the eighties at University College London, Space syntax research has mostly focused on configurational issues of the built environment, investigating the way people use space. One of the main findings of Space Syntax studies is that patterns of movement and interaction in buildings and cities are affected by the spatial layout, over and above effects from other spatial factors. Space syntax has been used in various case studies to assess layouts with an emphasis on understanding how people use, orientate and distribute themselves in space.

Space Syntax has developed a set of tools and computer modelling techniques for the analysis of space. The one mostly used for buildings is called Visibility Graph Analysis and deals with the analysis of visual fields, often referred to as isovists or viewsheds. An isovist, or viewshed, is the area of space directly visible from a location within the given environment. In architecture, Benedikt [10] was one of the first to introduce an analytical approach to space, using isovists as viewshed polygons that describe spatial properties from a given observation point, providing a subject-centred configurational approach to the experiencing of space. Space syntax analysis, in an attempt to describe space as a whole, without the local reference of the isovist, introduced a more general concept, the visibility graph [11]. This graph is constructed based on the inter-visibility of multiple isovists originating from all possible locations within a space. Visibility Graph Analysis (VGA) investigates configurational relationships using local and global measures of the graph. It has also been shown that visibility graph properties may be closely related to manifestations of spatial perception, such as way-finding, movement and space-use [12]. Case studies have illustrated the importance of isovists on the interpretation of spatial behaviour [13] while others have also revealed high correlations between visibility graph measures and the distribution of people within a building [14].

As far as visual field analysis is concerned, Space Syntax software tools mostly deal with space in two dimensions focusing primarily on the physical configuration of space and not on qualitative issues. Space is analysed mostly in terms of how much we see but not what we see-quantity of seeing rather than quality of seeing. Yet there is a potential of extending the research further by investigating qualitative issues of the built environment such as light.

4. The case study

In order to test the hypotheses on the effect of lighting on people's overt behaviour, a pilot study was proposed. The case study is the Royal Festival Hall in London. The setting was in an area adjacent to the northeast entrance of the ground floor and was used by the Royal Festival Hall as an information spot with display screens (or previously) printed panels, where the visitors could be informed on the programme of the day and other events that took place in the Southbank Centre (Fig. 1-2). During the planning stage of the case study, it was noticed that the area was not frequently used and that few numbers of people were consulting the information spot. The fact was acknowledged by the Royal Festival Hall people as well [15]. The arising argument was that the arrangement of the setting combined with the lighting was partly a causal factor. The question was whether a relighting of the setting would produce a different response from the visitors.

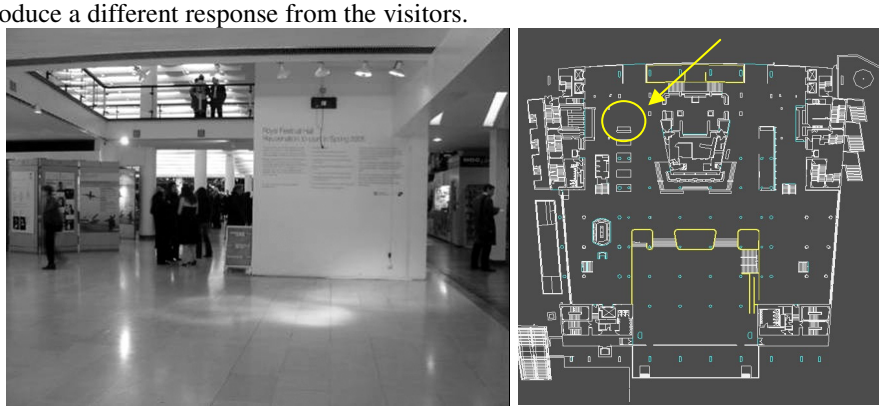


Fig. 1-2. The information area at the NW entrance of the building

The Royal Festival Hall is located on the south bank area of London and is part of the South Bank Centre which also comprises of the Queen Elizabeth Hall, the Purcell Room and the Hayward Gallery. Designed by London County Council, Leslie Martin and Peter Moro in the 50's, one of the goals was to make it an inviting venue "aiming specifically to allow visitors to spend long hours in the main foyer". The auditorium is enclosed within and above the public spaces and suspended over the main foyer and ballroom at entrance level, where informal events take place.

The building itself has a prominent location and nature among the South Bank Centre venues. Placed on a number of routes it often generates "through" apart from "to" only movement, making its role important in providing the visitors with information about events at the South Bank centre and cultural issues in general. The venue has generally high levels of use. Its public spaces are well used throughout the day with visitor numbers increasing significantly before and after the programmed events. Furthermore people make informal use of the space for meeting and recreation, making the venue a culturally and socially active one.

When trying to analyse the venue spatially based on the configurational properties, the main level of the Royal Festival Hall, shows a shallow core building (Fig.3). The most integrated part, both in terms of accessibility and visibility is the main foyer.

The foyer area, lies on major axes of the building, making its space directly visible and accessible from most entrances of the venue. Movement is gravitated towards there and then redistributed to other directions and destinations. In general, the whole main level of the Hall has good visibility with long views that extent to the outer limits of the building, facilitating movement and wayfinding (Fig.4).

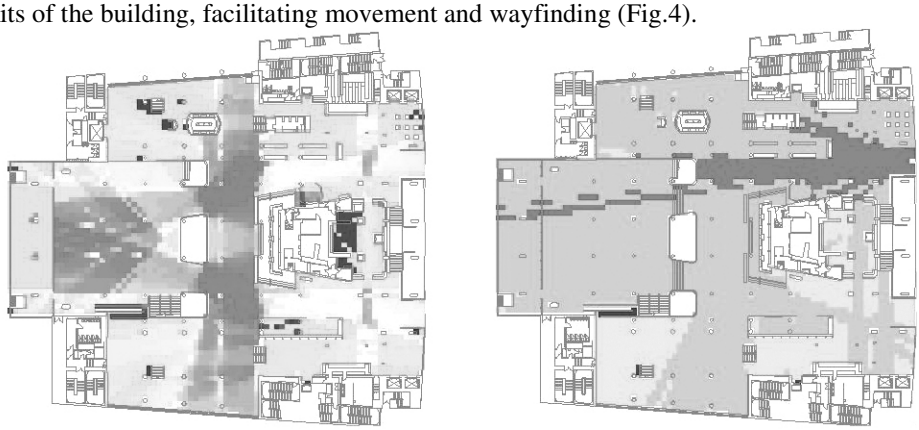


Fig. 3-4. Integration of the main floor and isovist analysis from the NW entrance.

Previous studies on the Royal Festival Hall have investigated the morphological characteristics of the public space in relation to patterns of space use. In a study by Doxa [16], spatial layout was analysed in relation to visitors' activities analysing the creation of formal and informal modes of communication. Spatial integration was shown to correlate with visitors' average degree of co-presence; co-presence used as a measure of the number of people directly accessible to a person at a location.

5. The methodology

In order to study the effect of lighting on the visitors' interaction with the setting, a series of relighting experiments were proposed, while observations studies took place both before and after the intervention to assess the impact of the lighting experiment.

A set of relighting experiments, altering the appearance of the space in terms of luminous pattern, light levels, spatial distribution of light and light source colour, was applied. Out of the theoretical potentials of relighting the space, the different lighting conditions were chosen in accordance to the requirements of the setting, availability of equipment available and the health and safety issues involved. Part of the design concept was also to take the original pattern off the floor, brighten the wall and enhance its height.

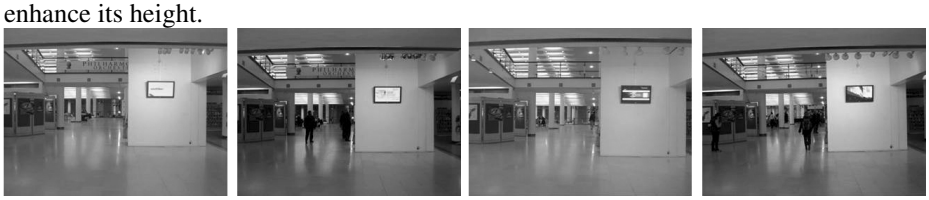


Fig. 5. The four different lighting conditions tested in the area

While representing and evaluating conditions of the setting, photometric measurements were taken both before and after the intervention. These included luminance, illuminance and chromaticity measurements. Luminance measurements were taken to plot the luminance distribution of the visual field at the most representative viewpoints and at the points of the movement flow from the entry point. In order to define these points, results from the pilot and previous studies [17] were examined, major movement routes through the study area were defined and the visual fields analysed.

As part of a pilot on the subjective assessment of the setting, questionnaires were also given to a number of visitors. The first part of the questionnaire referred to the visitors' profile while the rest comprised of questions trying to assess the informative process and the particular use of space.

Observations of visitors' movement and interaction patterns took place before and after the intervention to monitor the response and affect on space use. There was also an exploratory phase where informal observations took place in order to assess the requirements of the setting. All the observations were unobtrusive [18], and non-participatory in the interests of being non-reactive.

Movement tracing was the basic method used for observing the pattern of space use. People's movement through and around the setting was recorded and traced on the building plan for sets of 5 minute periods while the scale of the setting allowed for accurate and in detail recording.

Static snapshots were also taken at the beginning of each period of observation and along with interaction monitoring were the basic methods used to record activity in and around the setting, e.g. looking, reading, talking. This method was used to directly compare the movement and the stationary activity in order to assess the impact of the information spot on the stops of the movement flow. The presence of people and their movement was recorded and then plotted on a plan of the building, providing at the end several "photographic" snapshots of the use of space.

The "people following" method was also used as part of the pre-intervention study in order to investigate the general pattern of visit and people's pattern of info gathering throughout their visit. All these data formed a more coherent view of the way people interacted with the whole building and hence better explained the interaction at the setting at issue. Different categories of people were also observed at the preliminary phase such as: visitors, staff, men or women. Yet, after the emergence of the distinguishable pattern of the staff, they were omitted.

Several rounds of observations took place in order to cover different times of the day and during different kinds of events. Moreover the observation timetable was often amended according to the daily programme in order to monitor the setting both in busy and in quiet times of the day, e.g. pre-event, during event, post event periods, days with lunchtime free events or even days without major events.

In order to assess the way people interacted with the setting, a recording of the activity inside the study area took place. People were observed and while looking, reading, stopping or talking and the information was plotted on a building plan providing an activity mapping of the area. Especially for this recording, the use of a video camera was considered yet omitted as the data gathered were harder to extract than with real time observing.

6. The results

From the observations and the interaction monitoring it was apparent that the area works mainly as a passing through area yet differently according to the time of the day and the events that took place in the venue. Being just off the main circulation axis, it was used as an information area and a peripheral route choice for those who chose to look or read the info provided, a passing through area for those heading to the west side of the building and a waiting area for those meeting up friends before the events.

The people at the setting were identified according to their activity profile as seekers, explorers or connoisseurs. They were exploring, looking for something or moving in a definite way walking towards a destination. Human bodies and the way they distribute themselves in space can also affect the impression a space has on us. Bodies orientated towards the info spot, put the latter on the centre of the area while other distributions left the info spot on the periphery making the human body configuration the central piece.

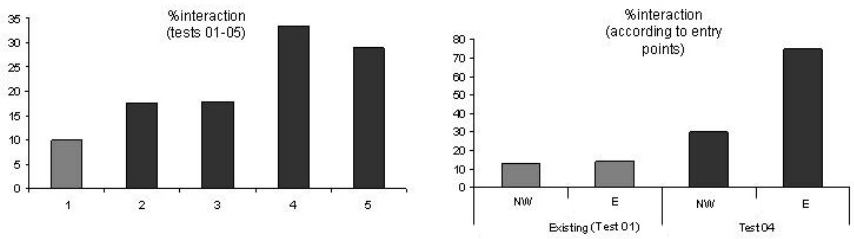
As far as the identity of the area was concerned, before the events happening at the RFH or during the intervals, the area works also as a stop or wait area, where people wait for people, meet, talk and interact. The information spot was lost at the periphery of the new identity of the space. In the pre-event period, the area was quite busy. Fewer people took notice of the info spot. Some read or looked at the screen while inspecting the surroundings during their wait. Yet people stopping or reading were not attracting others the same way as during daytime as they are less noticeable due to the business of the area. Also during the pre-event periods people were rushing and not taking the time to explore space, there was less interaction with the setting and less looking due to less exploration of the space.

Each time, the kind of the identity of the area was crucially defined by the type of presence of people, their spatial dispersion and their activity. As people looked for and followed people, more people would gather around waiting or chatting and more people would look and read the info screen. Yet, under the proposed lighting conditions, the identity of the area proved to be much more autonomous, as one of the goals of the design proposal was to take the info screen from the “periphery” of the area to the “centre” of it.

The results of the observation and movement tracing verified the initial assumption that the lighting arrangement of the setting was affecting the way people moved around the area. After the removal of the pool of light on the floor, whichever the lighting arrangement, it was observed that people were moving more around the area and were more probable to stay in read and interact with the setting. One assumption, in line with results from previous studies [3], is that people often prefer not to be in the spotlight. This fact relates to the notion that people like “watching the action” but to be off the spot.

The change of lighting in the area affected both the way people moved around and the way they interacted with the setting. They did cross or stay in the area more and they did look, read or interact with the info spot more. The most detectable change was on the route from the east side to the west of the building. While before the intervention only 9-21% of the people taking that route were looking at the information provided, after the intervention, the rate went up for every lighting

condition up to 75%. Indeed, this route is quite different to the main north-south route as the main features of the latter, such as the visual depth and the long isovists do not exist here. People entering the area from the east do not have the same depth attracting; neither have visual contact with a highly integrated space as the lobby. Their visual field is shallow and relatively dark. Therefore, areas of high contrast, such as the brightly lit screen, attract their attention. Also, from their position, they can see the lighting track used to light the spot, creating the impression of an exhibit. This concept of exhibit revealed to them, also offers a different understanding of the scene, urging them to look for the exhibit. On the other hand, people entering from the main entrance have a visual field which is dominated by the luminous depth attracting, the high, deep and luminous isovist leading to the foyer, making it much more difficult to change this balance and create a new attractor in the field.



Graph 1-2. Differences in interaction between different test conditions and entry points

7. The conclusions

As often the case in research, the way from the question to answer is usually not a straight one. Nor was it a straight one this time. Original thoughts and hypotheses were modified while other questions were defined on the way. The original hypothesis that lighting would affect movement patterns was tested and along with the results other governing and decisive factors came to light as well.

One striking and rather unexpected result was the accumulative effect of the presence of the people in the study area. People were attracted by people as the presence of a visitor inside the setting became an instant attractor to the rest. The info spot, from a “patterned surface”, became an interaction point - a stop with a possible meaning - and people were naturally interested to explore it too. The question therefore was redefined from what would attract people to what would attract the first one as the rest will follow.

The change of lighting conditions in this particular case did not seem to affect the general pattern of movement observed in the Royal Festival Hall, but it did affect the local pattern of movement. The observations showed that people walked more to and through the study area, where the light pool used to be, and were more probable to stay in the area while reading the information provided.

The numbers also show that there was a significant change in the interaction pattern. While before the intervention very few people noticed, looked at or read the

information provided, under the new lighting arrangements higher numbers interacted with the setting. People were not only looking more but the interrelations changed; relations between the screen, the area and the people. As a result, the qualitative configuration of the space changed and so did the social relations in it.

It can also be argued that under the tested lighting conditions, the identity of the area seemed much more focused to the curatorial goal, to make the area a well accessed and used info spot. The new arrangements took the info screen from the "periphery" of the area to the "centre" of it.

In general, the results argue that the alterations in the lighting conditions did affect to a certain extent the local pattern of movement and interaction. However one of the crucial factors of the actual interaction proved to be the identity of the presence of people in the area, which seemed to overcome any attempt to intervene with the setting.

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Challenges in Multi-level Wayfinding: A Case-study with Space Syntax Technique

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Abstract. In this paper we reanalyse an experiment on wayfinding in complex multi-level buildings in the light of formal measures derived from space syntax. The empirical study compared the performance of experienced and inexperienced participants in a set of wayfinding tasks, identifying specific strategies for vertical navigation. Inexperienced participants predominantly rely on a central-point strategy, while experienced ones have more accurate knowledge and plan more effectively. This is reflected by space syntax based route measures: routes of inexperienced users showed higher values of connectivity and integration as well as step depth to goal. Usability deficits of the complex building could be tied to formal analysis, revealing additional problems of the setting. Special emphasis is put on proper modelling of the vertical connections between floors in Visibility Graph Analysis. Based on the space syntax results, two layout redesigns are proposed that provide improvements both for general navigability and orientation at specific locations.

1 Introduction

Finding one's way around public buildings such as airports, hospitals, offices, or university buildings often proves to be a tedious and frustrating task. We aim to uncover the origins of wayfinding difficulties in a complex building setting by combining Space Syntax methodologies with psychological experimentation.

Hölscher et al. (2005) have presented an empirical investigation of wayfinding behavior in a complex multi-level setting, a conference centre. They were able to show distinct behavioural differences between study participant who had considerable prior experience with the building compared to inexperienced visitors and these differences could be tied to different navigation strategies employed depending on the level of familiarity with the setting. In the same study, a cognitive-architectural analysis identified a number of architectural peculiarities of the building (so-called *usability hotspots*) that appeared to hinder successful orientation and wayfinding.

In the present paper we will re-analyze the 2005 study based on a set of space syntax analyses of the setting. After briefly reviewing relevant literature on human

wayfinding in built environments we first describe the setting and the experimental procedures of Hölscher et al (2005) as a background for our investigation. This is followed by a formal analysis of the building with both axial line analysis and Visibility Graph Analysis (VGA). Based on the space syntax analyses, the usability hotspots of the building are reassessed and options for an improved redesign of the basic layout are evaluated. Finally the wayfinding patterns of the study participants are related to route-specific measures based on connectivity, integration and step depth to uncover task effects as well as group differences regarding familiarity with the building. Limitations of the approach and opportunities for future research are covered in the discussion section.

1.1 The Challenge of Wayfinding

Best's (1970) pioneering study on indoor navigation was the first to identify fundamental aspects of a building's route network, like choice points, directional changes and distances as relevant predictors of wayfinding difficulties in complex buildings. Weisman's (1981) identifies four general classes of environmental variables that shape wayfinding situations: visual access, the degree of architectural differentiation, the use of signs and room numbers, and floorplan configuration.

Another essential point seems to be the familiarity with the building. Gärling et al. (1983) point out that familiarity with a building has substantial impact on wayfinding performance. So does visual access within the building: If large parts of the building are immediately visible and mutual intervisibility (vistas) connects the parts of the building, people have to rely less on stored spatial knowledge and can rely on information directly available in their field of vision. A disadvantage of these lines of research is that floorplan complexity and configuration as well as visual access have been defined rather informally in the literature discussed above (e.g., by subjective ratings). The concept of *isovists* (Benedikt, 1979) provides a much more precise mathematical framework for capturing local properties of visible spaces, which correspond with psychological measurements of environmental perception (Stamps, 2002). Space syntax (Hillier & Hanson, 1984) has introduced formalized, graph-based accounts of layout configurations into architectural analysis. Calculations based on these representations express the connective structure of rooms and circulation areas in a building and are strongly associated with route choices of hospital visitors both in unguided exploration and in directed search tasks wayfinding behavior (Peponis et al., 1990; Haq & Zimring, 2003). Yet research along this methodology is generally based on correlations of building layout and aggregate movement patterns, thus providing no immediate understanding of individual cognitive processes (Penn, 2003). Recently, Hillier and Iida (2005) have presented initial approaches to close this gap.

1.2 Wayfinding Strategies for Multi-level Buildings

Hölscher et al. (2005) provide an overview of the types of knowledge and the navigation strategies people employ in complex multi-level buildings. Depending on the degree of familiarity with the environment people use strategies of varying

complexity: Novice users are most likely to follow a *central point strategy* of finding one's way by sticking as much as possible to central, well-known parts of the building, even if this requires considerable detours. More complex strategies include the *direction strategy* of choosing routes that head towards the *horizontal* position of the goal as directly as possible (Hochmair & Frank, 2002; Conroy Dalton, 2003), irrespective of level-changes. By contrast, the *floor strategy* is to find one's way to the floor of the destination first, irrespective of the horizontal position of the goal. People familiar with the building tend to rely on either of the two later strategies. Often they also have full knowledge about the building topology, making complete path planning feasible as an alternative to these heuristic strategies.

1.3 Aims of the present study

Navigation in multi-level buildings has received relatively little explicit attention in wayfinding cognition research as well as in the space syntax community. For both areas, handling the third dimension of stacked floors has been problematic. The navigation difficulties of the multi-level building in the present study clearly stem from vertical travel. Therefore it appears extremely relevant to carefully model the vertical connections in a set of space syntax analyses of the building.

Can Space Syntax account for wayfinding behavior? Wayfinding research has the distinct feature of providing data on purposeful travel between destinations of individual study participants with known behavioural goals. Therefore it appears necessary to capture the properties of *path sequences* rather than only looking at the spatial properties of single points or areas. We present initial attempts towards this end and test how *route-based measures* can account for the behavioural data.

Can Space Syntax help to identify and explain wayfinding problems? On the practical side, we aim to find objective measures of usability deficits of this setting.

2 Wayfinding Experiment

In this section we recapitulate the setting and experimental procedures of the original study by Hölscher et al. (2005) and describe additional procedures for the new analyses presented in the current paper.

2.1 The conference centre

The Heinrich-Lübke Haus, a conference centre, was built in 1970 in Günne, near Düsseldorf, Germany. The ground floor (level 0) of the multi-functional building illustrates the general characteristics and spatial organization of the layout (see Fig. 1). The basic structure consists of various simple geometrical elements that are arranged in a complex and multi-faceted architectural setting. This building is subdivided into a well-designed group of solids with void space between them. The building could be architecturally categorized as an "indoor city" (Uzzell, 1995) as it is composed of a small ensemble of units and a large public circulation area. Each group

of solids implies various functions, e.g., the living quarters (C) have a quadratic design style and the communication area (D) a hexagonal design style. The main path of walking through the building is an axial one rather than a cyclical one.

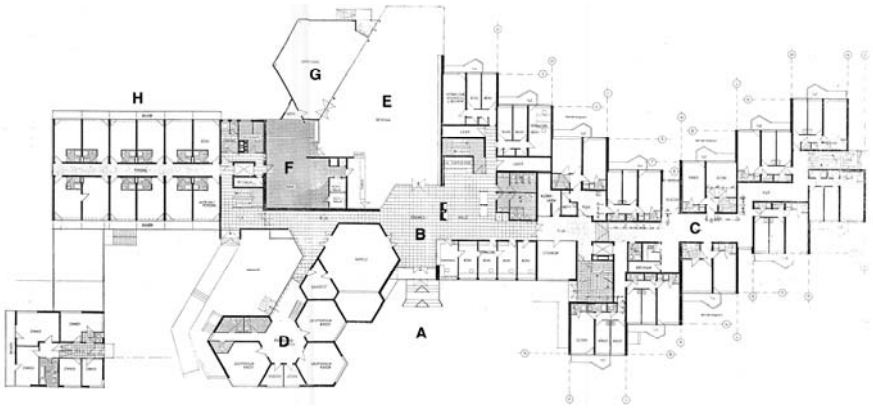


Fig. 1. plan view of ground floor: (A) main public entrance (B) entrance hall (C) living quarters (D) Commons – communication and conversation area (E) dining-room (F) kitchen (G) coffee bar (H) lecture rooms.

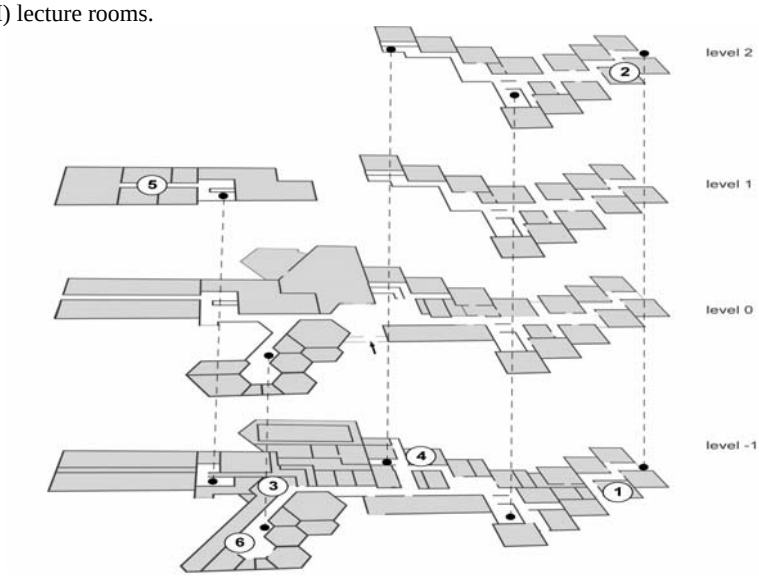


Fig. 2. The floors of the building with circulation areas. Stairways are illustrated as vertical connections. Starting points and goals of the navigation tasks are marked by numbers (example: "1" marks the starting point for task 2 and "2" marks its goal).

Changing floors in the building reveals its spatial complexity and vertical impenetrability. As one can see in Figure 2 the layout of the hallways on every floor may appear to be locally one and the same for a casual user, but is actually different for each floor. For example, the configuration of the ground floor (level 0) and the basement (level -1) differs significantly. The consequences of this and related structural deficits of the building will be discussed as *usability hotspots* in section 4.1.

2.2 Participants

Seven women and five men in their mid-twenties to mid-thirties were recruited for the wayfinding experiment during a cognitive science summer school. Six of them were familiar with the building. They had previously visited the one-week conference at least twice. The six participants unfamiliar with the building (three of them were women) visited the conference for the first time. Their sessions took place within the first three days after arrival.

2.3 Procedure

In this building, the participants' task was to find six locations. The participants were filmed with a camera and had to verbalise their thoughts. During the whole experiment participants were not allowed to use floor maps or ask other people for advice, but they were allowed to use signs or to look out of the window for orientation as long as they stayed inside. All participants received the tasks in the same order, as each destination point is the start location for the following task, making randomization unfeasible. Navigation tasks were as follows (see Fig. 2):

1 From outside the building, the participants were shown a wooden *anchor* sculpture inside the living quarters. They had to find it from the main entrance without leaving the building again.
2 The goal was to find *room 308.*
3 Participants had to navigate to the *bowling alley*. It was located in the cellar of the building, where the locations for all leisure activities were to be found.
4 The *swimming pool* could also be found there.
5 The participants had to navigate their way to the *lecture room number four.*
6 The final navigation task's destination was the *billiard table.*

2.4 Data analysis

Performance measures: For each task, the shortest route as well as a list of reasonable route alternatives was determined beforehand. Reasonable routes are defined as neither containing cycles nor dead ends or obvious detours.

Navigation performance was measured with six variables: (1) time to complete the task, taken from the video; (2) stops; (3) getting lost, i.e., number of times participants left a *reasonable route alternative* and showed detour behavior; (4) distance covered; (5) distance covered divided by length of the shortest possible route. (This parameter expresses the proportion of superfluous way independent of task length. E.g., a value of 1.35 can be interpreted as walking 35% farther than necessary); (6) average speed.

Path choice sequences: Based on the video-recording of each session, the walked route for each participant and each task was hand-drawn into printed plans of the building. This was used to determine distances of routes and superfluous way after getting lost (see above) as well as the position & duration of stops. Coding was done by two independent raters. In addition to the data processing for the Hölscher et al. (2005) analysis, further coding was necessary: To relate the behavioural data with the

Space Syntax analysis of the building, we performed a detailed coding of the individual routes each participant took in each task. The route network in the building was segmented as illustrated in figure 9. The segments represent cognitively plausible subsections of the corridor network and correspond to decision points in the route network. With this coding scheme, the sequence of path choices is translated into a string of visited segments for each task and each participant.

3 Architectural Analyses

The formal architectural analysis consists of three parts. The *axial line analysis* (Hillier & Hanson, 1984) accounts for important aspects of the overall structure of the building. The more detailed *Visibility Graph Analysis* (Turner et al., 2001) is especially relevant for the analysis of the usability hotspots as well as the evaluation of two usability-oriented layout redesigns proposed by the authors. Also, the VGA is the basis for investigating the relation of *behavior sequence data & spatial properties*.

3.1 Axial Analysis

For the axial line analysis, the Space Syntax software *Depth Map* (Turner, 2004) was used. One of the key aspects of the analysis was to account for the building's multi level structure. Chang & Penn (1998) represented vertical interconnections by means of weighted links between floors. Our analysis uses an additional axial line for each connection between two floors. This additional axis is manually connected to the corresponding lines in the upper and the lower floor. Figure 3 shows the floor plan of the building together with the axial map and the manual connections.

The axial map is intended to reflect the effective visibility structure when navigating the building, instead of being an ideal fewest and longest lines map. The most important consequence of this decision is to represent the main corridor (in the ground floor and in the basement) by two main axes although, in theory, one long line would be possible. In practice however, the main corridor is perceived as interrupted. Figure 4 shows the axial line of the *navigation space* in the building.

A generally remarkable result with respect to wayfinding and usability issues is the poor *intelligibility* score (correlation of connectivity and integration) of the complete system, namely 0.15 (total no. of lines: 79). Analysing each floor separately, the ground floor and basement revealed substantially higher intelligibility scores (.53 & .71), unlike the first and second floor (.09 & .016). An axial map adding *all publicly accessible* rooms revealed an even poorer intelligibility of 0.12 (total no. of lines: 105). No major differences with respect to spatial variables between these two analyses were found. We will only refer to the analysis of *navigation space* below.

3.2 Visibility Graph Analysis

Compared to the axial lines, *visibility graph analysis (VGA)* provides a more fine grained representation of architectural space. The visibility graph is based on a two

dimensional grid of points which fills all open space to be considered. Two nodes are connected if and only if the corresponding locations in space are mutually visible. Again, Depth Map (Turner, 2004) was used for the VGA. The *step depth* between two locations *a* and *b* is defined as the number of edges on the shortest path between *a* and *b* in the visibility graph. This measure reflects the number of turns required to get from *a* to *b*. *Connectivity* or *degree* of a node *n* is a local measure which captures the amount of space directly visible from *n*. The global measure *integration* is a normalized version of the mean depth of a node *n* to all other nodes in the system. Intuitively integration reflects the centrality of a node with respect to the whole graph. For details on these measures please refer to Turner (2004; Turner et al., 2001).

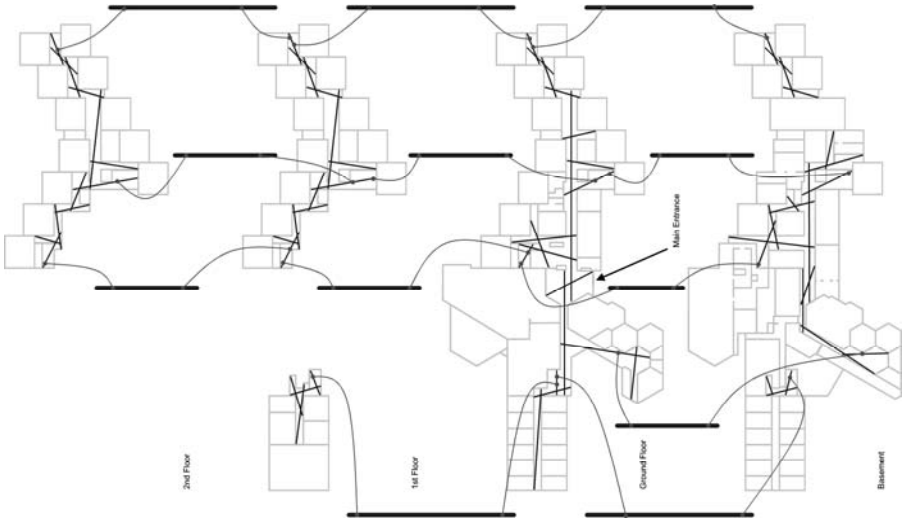


Fig. 3. Axial lines in the navigation space (corridors & stairs). Manual links are shown with green lines, axes connecting floors are drawn in bold.

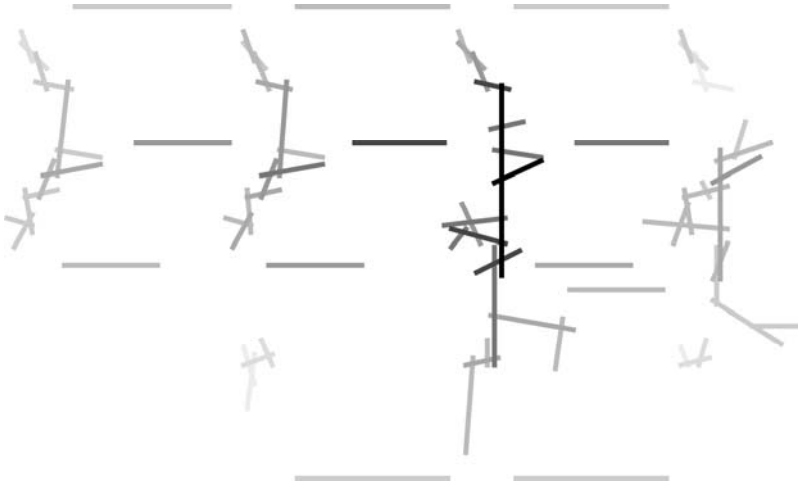


Fig. 4. Axial line Integration, Navigation Space.

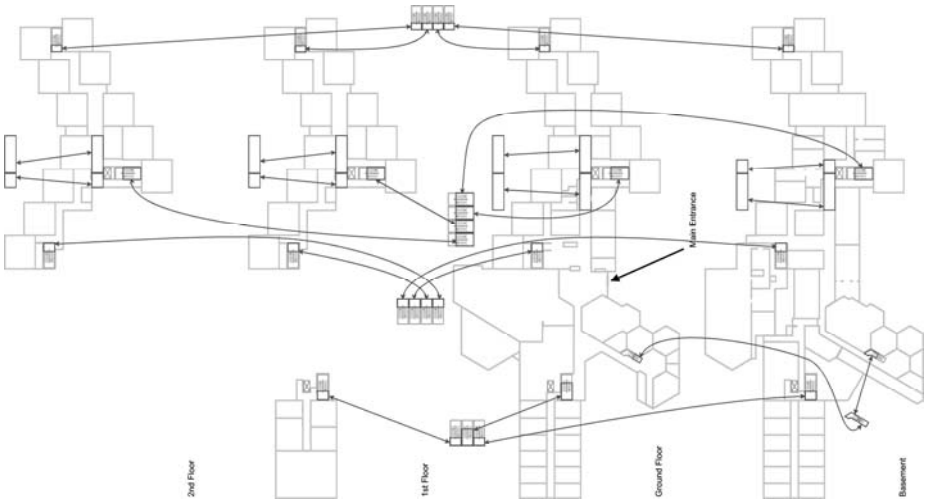
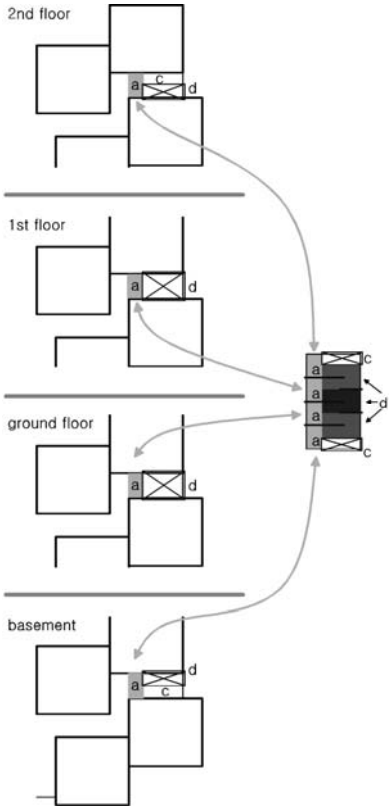


Fig. 5. Manually generated connections & areas of vertical interconnection between floors for Visibility Graph Analysis.



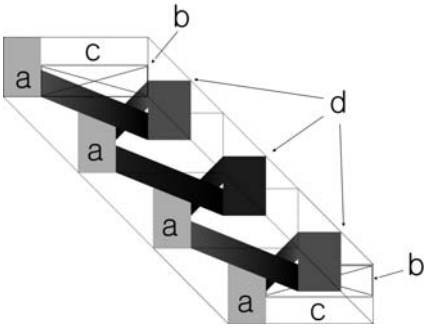


Fig. 6a. Top right: Schematic view of a staircase. **Fig. 6b.** Left: Two-dimensional representation of the vertical interconnections via widgets and manual links. The floor plan of the staircase is shown as well as the widget representing the vertical interconnection between the stairs. Letters and colours help matching space in the schematic 3D view with the two-dimensional representation. (a) Space merged between floor plan and widget space. (b) Space under the stairs in the basement and on top of the stairs in the upper floor is not represented. (c) Space represented in the floor plan but blocked in the widget. (d) Space represented in the widget but blocked in the floor plan. Colours identify stairs.

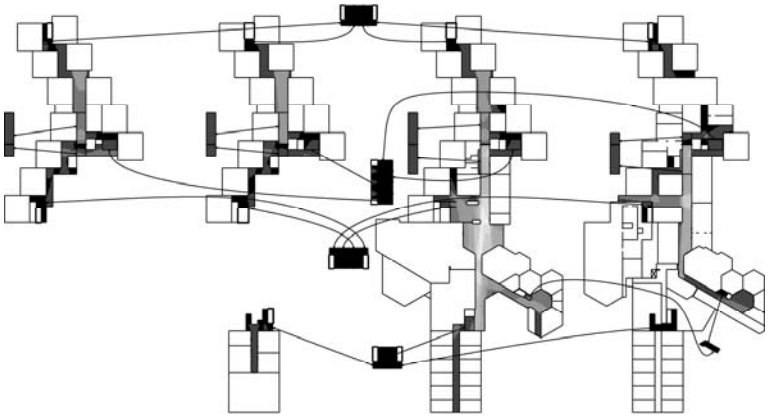


Fig. 7. Visibility Graph Analysis (VGA): Navigation space; Connectivity

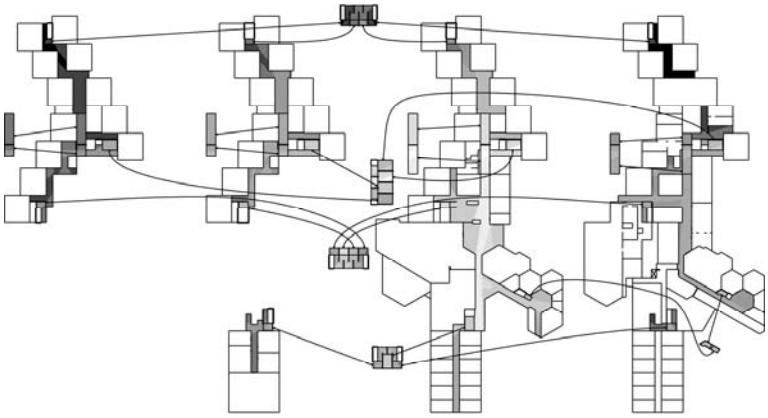


Fig. 8. Visibility Graph Analysis (VGA): Navigation space; Integration (HH)

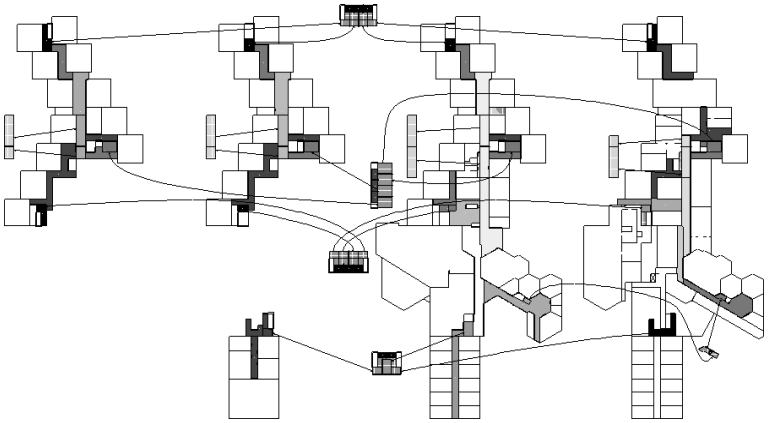


Fig. 9. Segmentation for behavior sequence analysis. Levels of gray represent the mean *connectivity* of each segment (based on VGA).

We have identified the vertical structure of the building as a crucial factor in understanding its behavioural consequences. Since Depth Map supports two-dimensional visibility graphs only, the analysis is based on separate floor plans for each building level. Vertical interconnections in the staircases were modelled with the help of *widgets* providing horizontal space with representative intervisibility structure. Visibility graph nodes in the floor plan were manually connected with those in the widget representing the staircase. With respect to the intervisibility in the widget space it was ensured that there is no direct connection between the lowest and the highest floor. E.g., the visual step depth between floors increases with the number of levels to traverse. When designing the staircase widgets it is important not to change the amount of space in the visibility graph. Basically, the widget duplicates the staircase area in the floor plan. To compensate for this, space in the staircase either

- has to be *merged* via manual connection (making it count only once in total) or
- has to be blocked in the widget or
- has to be blocked in the floor plan.

Figure 6 shows a schematic view of a staircase and how different areas are captured in the two-dimensional space of Depth Map for the VGA. Similarly, a set of steps (covering ca. 120 cm vertical height difference; within-level) in the main corridor towards living quarter was bridged with a corresponding widget area.

3.3 Visibility Graph Analysis & Behavior Sequence Data

As described in section 2.4, participants' trajectories were recorded in terms of sequences of visited building segments. To relate participants' routes to different spatial measures of the architectural analysis, each behavior sequence was evaluated based on average syntax values of the visited segments.

The first step of the calculation is to determine the average *connectivity* and *integration* values for each building segment, based on the VGA values of the points in the respective segment. In the same way, the *step depth* of a segment was calculated by averaging the step depth of the points in the segment to the destination of a wayfinding task. By this, six values were obtained for each segment, each reflecting its distance to one of the six navigation task destinations.

The result of this first calculation is a set of values associated with each segment. Connectivity and integration reflect *general spatial properties* of a segment. By contrast, the *step depth to destination* values are *task specific* measures.

The second step is to relate participants' individual routes to the syntax properties of the building. To do this, the following measures were calculated for each behavior sequence in each navigation task:

- *Mean Connectivity in Route:* The connectivity values associated with the segments in the route were averaged[1].
- *Maximum Connectivity in Route:* The highest connectivity value of the segments in the route.

[1] Note that the connectivity value associated with a segment is itself a mean value of the connectivity of all graph nodes in this segment.

- *Mean / Maximum IntegrationHH in Route:* These two values are calculated in the same way as the connectivity values.
- *Mean Step Depth in Route:* The step depth of each segment to the destination is averaged. It is important, that the mean step depth of a route is calculated with the step depth values of the corresponding task destination. E.g., a route of navigation task 1 receives the average step depth of all its segments to destination of task 1. This measure reflects, how far away[2] from the destination the route is on average.
- *Maximum Step Depth in Route:* The maximum step depth of the segments in the route to the corresponding destination. This measure reflects the step depth of the segment most far away from the destination.

4 Usability Hotspots & Layout Redesigns

4.1 Hotspots

The analysis of usability hotspots reported in Hölscher et al. (2005) was based on a qualitative expert evaluation of the building by the architect in the research team. To some extent the results were substantiated by relating behavioural measures like stops and detours to specific point and areas of the building. The current analysis uses the original qualitative analysis as input and tests how space syntax techniques can link these observations to concrete, objective measures of the building.

Overall, we believe the functional dilemma of this building for wayfinding is prominently caused by the problematic arrangement of complex decision points, their linking paths, the position and design of stairways, vertical incongruence of floors, incomprehensible signage, and too few possibilities for monitoring interior and exterior landmarks. Consequently, the building as a whole gives the impression of a three-dimensional maze. In the following, we focus on seven "hotspots" of the building and relate their disadvantages to formal analytic measures.

Hotspot 1: Entrance hall: The public entrance (see Fig. 1, A) as well as the large entrance hall (Fig. 1, B), are rather indiscernible, despite being centrally located in the general configuration of the building. An essential function of the entrance hall is to be readable as such and to cognitively structure the route network, especially for unfamiliar visitors, who tend to rely on central points for their navigation strategies.

The usability deficit of the entrance hall is maybe best illustrated by Figure 10, representing the direct visibility (step depth = 1) for several points in the entrance hall along a typical trajectory. For the user entering the entrance hall, the visual access changes very rapidly and at no point all relevant navigation choices are visible simultaneously. Especially the visual connection to the nearest staircase (next to the cafeteria area) is never properly made. The navigator has to leave the entrance hall to gain visual connection. More generally speaking, the entrance neither contains the most integrated nor the most connected areas of the navigation space in the building (see Fig. 7 & 8). Overall, the entrance hall doesn't make the navigation choices salient to the user; connections to all stairways are invisible from the entrance hall.

[2] „Far away" in terms of step depth that is number of edges in the grap or number of turns.

Hotspot 2: Survey places: The building lacks survey places. While the entrance hall fails to visually connect to relevant decision points like stairs, lack of survey options is pronounced throughout the building. The only visual connections between floors are by staircases, the majority of which is separated from the corridor network by glass doors. There are no open connections like galleries, ramps or openly visible stairs. Lines of sight within floors are broken by (mostly 90°) zigzag turns and small corridor diameters. The lack of survey was identified to be particularly evident for the basement in the previous study, with more stops / hesitations observed in the basement compared to a matched area in the ground floor (near entrance hall) paralleled in size and alternatives. The visible area from any given point is captured by the VGA connectivity measure, representing the isovist area around it. As can be clearly seen in figure 7, the navigation space in the basement as well as in the corridor networks of the higher floors provides almost no positions that can be characterized as providing overview.

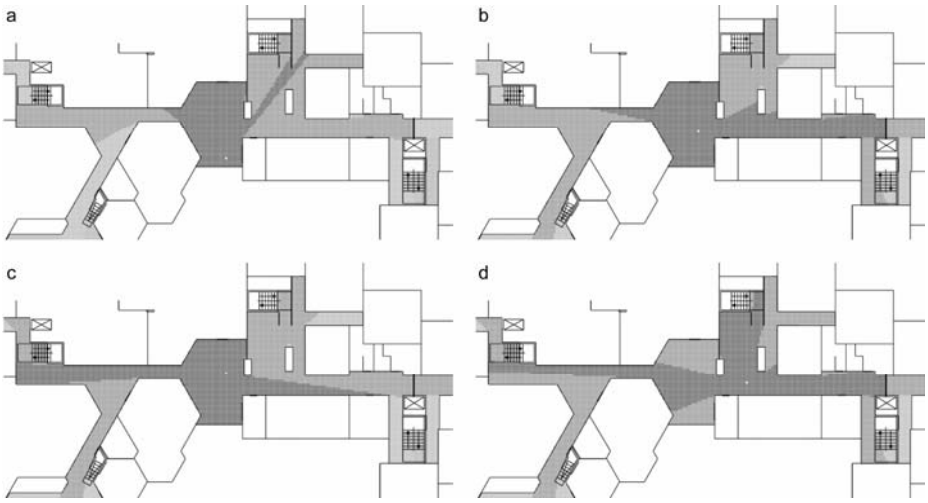


Fig. 10. *Entrance hall*: Step depth from selected points (white dots) along a trajectory into the building, from the entrance (a) through the main hall towards the stairs (d).

Hotspot 3: Incongruent Floors: The floors in this building provide very incongruent layouts. For a person standing in the building, the floors of the conference centre *locally* give the impression of matching one another (especially in the living quarter area), but in fact the hallways are considerably different. From wayfinding research this is expected to prompt inadequate assumptions about the route network. While the incongruence of the floors is apparent without a formal building analysis, the stark differences between floors in the distribution of connectivity and integration (*see figure 7 & 8; VGA navigation space)* underscore the problem of confusing the user. A person who quite naturally assumes congruent floors (see Soeda et al., 1997), will form false expectations about the connectivity or integration properties of his surrounding in this setting.

Hotspot 4: Dead ends: Dead ends seriously complicate wayfinding, as they block the user's exploration activity and make it difficult to form a proper mental representation of the overall path structure. For the analysis, we differentiate two

types of dead ends, *apparent dead ends* and *real* ones. The public area surrounded by the living quarters leads to a dark, uncomfortable corridor with zigzag turns, making it a good example of an *apparent dead end*. Users will not expect the stairways at the end of the corridor (far right, Fig. 1) and thus miss relevant route choices. Going down the corridor requires the users to navigate against a step decline in connectivity and integration (Fig. 7 & 8). In task 1 this corridor is the only option towards the goal, and most study participants were initially very reluctant to follow this path.

The behavioural consequences of real dead ends are more pronounced. We observed a total of 17 episodes of getting lost in our experiment. Five of these episodes (29%) were directly caused by the fact that the participant was stuck in one of the two dead ends in the basement (the far right and far left parts of the basement level in Fig. 2). In the VGA of the navigation space (Fig. 8) as well as the axial line analysis (Fig. 4), these dead ends are reflected in extremely low integration scores of these areas, especially for the dead end in the living quarter.

How difficult is it to overcome these dead ends? For our analysis we treat the dead ends as blockages in the path network and measure the step depth from one end of the blockage to the nearest navigable point on the other side. The step depth between both sides of blockage below the living quarter is 17, the step depth below the lecture rooms area is 8. This is an illustrative measure for the detour that a user of the building has to make if he erroneously runs into the blockage. A remedy for this substantial detour problem is presented in section 4.2.

Hotspot 5: Interior building structure: Looking at the ground plan (see Fig. 1), the dissimilarity of geometrical shapes and architectural forms would appear to be helpful for the users to orientate themselves. But in fact, when actually navigating in the building, the different subsections (except for semantically rich areas like the entrance hall, the cafeteria or specific leisure facilities) are no longer readily recognizable for the inexperienced building user, leading to a lack of visual differentiation (Weisman, 1981). While this problem is likely related to *hotspot 2*, the lack of survey, we have yet to identify space syntax measures that would capture this problem adequately. On a more general level, the extremely low *intelligibility* score of (.15 in axial line analysis) can be seen as an indicator of a suboptimal path structure.

Hotspot 6: Public and private space: Further wayfinding problems are related to the differentiation of public and private space. Haq & Zimring (2003) have pointed to differences in space syntax properties of the public and non-public circulation networks of hospitals and possible consequences for building navigability. We have generally limited our investigation of this conference centre to those areas that the visitor of the building may enter. In fact, the personnel of conference facility have two additional corridors available. Ironically, these directly bridge the dead ends identified above. We interpret this as an indicator that the planning of public and non-private space was inadequate. By putting storage space and service corridors in positions where they essentially block public circulation, navigability was seriously hampered.

Hotspot 7: Stairways: In general, stairways should help integrating vertical information while exploring multilevel buildings and they should ease experiencing the layout spatially with respect to the building as a whole. When planning the design of staircases architects generally have to take into account two key design parameters. First the constructional and representational form of its appearance have to be highlighted with respect to the function of the building and second the position of the

stairway has to be optimized in relation to the user' s activity within the layout. The positioning of the stairs in the building is critical. As we have seen with *hotspot 1*, the entrance hall, none of the five staircases is directly visible from that central area.

Behaviourally, the foremost stairway (near the entrance hall) was most problematic. This deficit is partly due to the complete lack of visual access to the outside, which would help to improve spatial updating. Additionally, the number of rotations within the stairway plays a great role for the user's stability of his cognitive map of the building (see Richardson, Montello & Hegarty, 1999, for further research into the consequences of rotations in vertical movement). This staircase is offset from the main axis requiring numerous turns when moving between the main corridors of two levels. Frequently, users reported being very disoriented after using this stairway. Six of the seventeen episodes of getting lost (35%) are identified as disorientation observed directly after leaving the stairway, sometimes even before reaching the proper destination level. The axial line analysis (Fig. 4) provides a numerical measure for this challenge: one needs to travel along a minimum of 7 (!) axial lines to move from the entrance hall to the corresponding main intersection in the basement.

Furthermore, there is no main stairway serving as the user's structural focus while exploring the building. In debriefing interviews users reported little sense of a *main stairway*. The VGA analysis of integration (performed separately by floors) provides a potential explanation: The integration values of the two most centrally located staircases fluctuate widely between floors: While the stairs closest to the entrance have higher integration values compared to the second-closest stairs (Fig. 1, lower right) on the ground floor and in the basement (6.7 vs. 5.9 and 6.9 vs. 5.8), the pattern switches around on the upper floors (2.8 vs. 5.2). Thus the stairs have different roles for the different levels of the building.

Structurally, the problem of choosing the proper staircase is increased by the fact that not all stairs connect to all floors or even all parts of individual floors (axial line analysis, Fig. 4). Taken together, the analyses revealed that - except for global building characteristics - the staircases are the single most clearly identified cause of wayfinding problems in our setting.

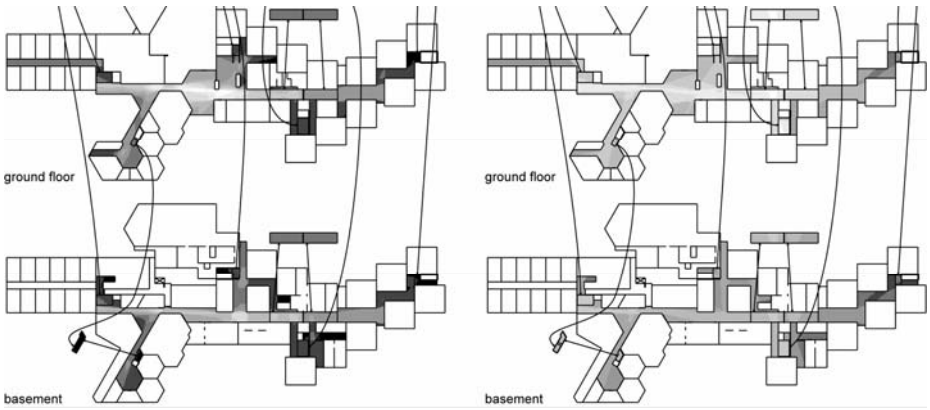


Fig. 11 & 12. "Congruent Layout" Improvement: Connectivity (left); Integration (right).

4.2 Layout Re-designs

Based on the hotspot analysis, we have worked out two very simple variations of the layout. We do not claim any architectural soundness in these re-designs (e.g., aesthetics, structural engineering, or functionality), they are simply proofs-of-concept for addressing wayfinding problems. One of the variations is an attempt to overcome the dead ends in the basement by copying parts of the fully connected layout from the ground floor to the basement. The second variation addresses the problematic entrance hall by opening visual connections to the centrally located stairs.

Congruent Layout variation:

The congruent layout variation closes the dead ends (hotspot 4) and addresses the public-private space conflict (hotspot 6) as well as interior building structure (hotspot 5). Figures 11 & 12 depict the resulting connecti-vity and integration distribution in this new layout. This intervention eliminates the segregation of the formerly dead-end areas, providing a much smoother gradient of connectivity and integration for the basement. The main corridor becomes much more legible and we find a clear focus of connectivity at the main T-intersection in the basement. In axial line analysis, the integration value of the originally least-integrated axis (at the dead end) of the basement improves from .36 to .72.

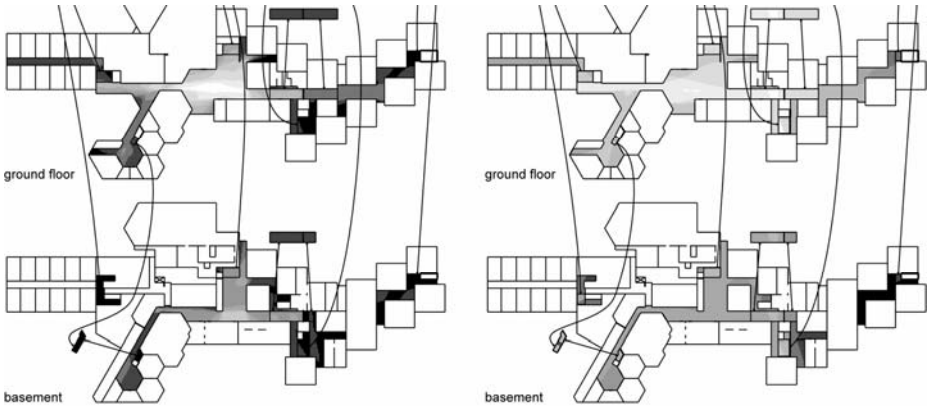


Fig. 13 & 14. "Visual Access Layout" Improvement: Connectivity (left); Integration (right)

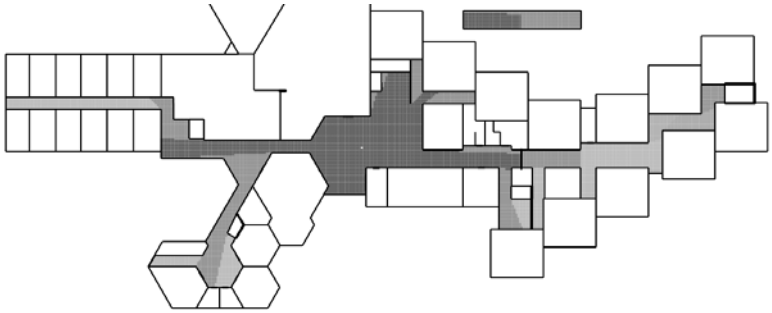


Fig. 15. "Visual Access Layout" Improvement: Step depth from center of entrance hall.

Visual Access Layout variation:

This variation opens the visual barriers in the top right corner of the entrance area (hotspot 1) and removes visual clutter in the adjacent area of the centrally-located staircase (hotspot 7). Similarly, we provide a large area of visual linkage between this staircase and the central pathway in the basement (hotspot 2). While in the original layout the stairs are separated by a glass cage, this is removed in the re-design. Figures 13-15 illustrate the resulting situation with respect to connectivity, integration and step depth from the entrance hall. A direct connection to the stairs is established (Fig. 15). The centre of connectivity moves to the entrance hall. While the highest integration level is still located further to the right, an area of high integration emerges in the entrance hall. Compared to the original layout, the correlation of connectivity and integration in VGA improves from .29 to .37. Local visibility now corresponds more closely with the global connections in the building.

These analyses can be seen as initial support for the potential usefulness of layout improvements along these lines. Naturally, the improvements have yet to face empirical testing. We intend to transfer these layouts to a Virtual Reality experiment environment and run comparative tests in the near future.

5. Wayfinding Behavior

5.1 Task Difficulty

Table 1. Step depth between start and destination point of each task and the corresponding performance in each task. The rightmost column indicates the correlation of step depth the corresponding performance measure. An asterisk* marks a significant difference (p<.05), a cross† marks a statistical trend (p<.10).

	task 1	task 2	task 3	task 4	task 5	task 6	correlation with step depth
step depth	12	10	14	2	9	9	-
time [s]	226	78	159	34	103	81	.78 †
stops [n]	2.8	0.4	1.7	0.3	0.5	0.9	.65
getting lost [n]	0.7	0.1	0.5	0.0	0.3	0.2	.77 †
distance [m]	168	84	127	40	113	87	.83 *
way/shortest way	1.68	1.24	1.71	1.00	1.08	1.50	.82 *
speed [m/s]	0.74	1.08	0.81	1.28	1.12	1.10	-.87 *

In this section we reanalyze behavioural data from Hölscher et al. (2005) in the light of the spatial analyses provided in the previous sections. In table 1 we compare the performance measures with the step depth of each wayfinding task, effectively a measure of the number of turns required to get to the goal location. The general pattern of difficulty observed in the earlier study clearly corresponds with the step depth between origin and destination point of the individual tasks. This is reflected in strong correlations of step depth with the performance measures, ranging from .65 to

(-).87[3]. Overall, the pattern of difficulty of the different tasks is clearly captured with the step depth measure.

5.2 Sequences & Expertise

Hölscher et al. (2005) identified significant differences in the navigation behavior of experts and novices across all performance measures (Table 2). Our reanalysis intends to uncover to what degree this can be captured by space syntax based route measures.

Table 2. Means and standard deviations of the performance of novices and experts and VGA measures for the corresponding path sequences, averaged across tasks. An asterisk* marks a significant difference (p<.05), a cross† marks a statistical trend (p<.10).

	novice user		experienced user	
Performance	m	sd	m	sd
time [s] *	128	22	95	21
stops [n]	1.36	0.69	0.78	0.80
getting lost [n] *	0.42	0.17	0.17	0.21
distance [m] *	115	16	89	17
way/shortest way*	1.55	0.22	1.17	0.16
speed [m/s] *	0.96	0.06	1.10	0.09
VGA measures				
Mean Connectivity in Route *	707.18	32.25	668.74	20.08
Max. Connectivity in Route *	1528.42	103.15	1424.49	40.37
Mean Integration HH in Route †	2.067	.050	2.018	.059
Max. Integration HH in Route *	2.639	.112	2.496	.075
Mean Step Depth in Route †	5.131	.540	4.692	.421
Max. Step Depth in Route	8,939	.392	8.494	.804

We hypothesize that experienced and inexperienced users differ in the cognitive basis of their navigation decisions. Experienced users are likely to know the exact location of the target destination. They can plan their path from memory and do not have to rely on local or configurational features of the environment. Novices, by contrast, often do not know the position of the target exactly and rely on information made available by their surrounding. Thus we expect novices on average to more closely follow the pattern of connectivity and integration in the building, preferring to travel along path with higher values on these measures, while experts should be less susceptible to such influences. Instead, we expect experienced users to more directly travel towards the goal location, irrespective of local travel choices. This should be reflected in lower scores for the average step depth between each location in their

[3] The correlation with speed is negative, because only for this measure low scores indicate high performance. Note, that data was aggregated over participants for this analysis, to avoid overestimating correlations based on autocorrelations within participants across tasks. For the same reason, data for the group comparison (t-tests) in section 5.3 was aggregated over tasks.

path and the target location of each wayfinding task, since experts should choose path segments most directly connected to the goal.

The analysis of the sequence data with route-based space syntax measures is in line with these hypotheses: The mean connectivity of path segments traversed in a route by novices is significantly higher than for experienced users (t(10)=-2.47, p=.017; all tests one-tailed), also the maximum connectivity is significantly larger for novices (t(10)=-2.30, p=.029). The mean integration of path segment traversed by novices vs. experienced users shows a statistical trend in the same direction (t(10)=-1.50; p=.082), and the maximum integration on a route is again significantly higher for novices (t(10)=-2.58; p=.014). Looking at average and maximum step depth of route segments the corresponding target location of each task, the opposite pattern emerges qualitatively: While the novices more often traverse locations more distant from the target location (maximum step depth), experienced users show at a least a statistical trend of avoiding such deviations throughout their path choices compared to novices (mean step depth; t(10)=-1,57; p=.074).

Table 3. Frequencies of strategy selection in novices and experts.

	novices	experts	sum
direction strategy	8	6	14
floor strategy	7	12	19
central point strategy	13	1	14
route is well-known	2	12	14
Sum	30	31	61

Upon closer inspection of the sequences in the building, we were able to pinpoint specific areas in the building that largely contribute to these differences. The novices more often travel through the highly connected and integrated areas in the entry-level floor, the entrance hall and the highly integrated staircase. In terms of navigation strategies, this reflects the *central-point strategy*, most prominent among novices and least popular among experts (see table 3). The experts, by contrast, most often knew the exact position of the goal location, which allowed for a strategy based on complete path planning, following a steeper gradient of step depth reduction. Thus, the different space syntax properties of the route choices of novices and experts can actually be tied to different navigation strategies.

6 Discussion

In sections 5 and 6 we have successfully connected behavioural data from a wayfinding experiment to formal spatial analysis of the setting. The majority of the usability hotspots in the building could be clearly linked to space syntax measures of step depth, connectivity and integration. As expected, the step depth measure captured issues in local visibility of the entrance hall and staircases, while the integration measure was sensitive to more general structural deficits in the building, like dead ends and incongruent floor layouts. Compared to the original analysis in Hölscher et al. (2005), we were not only able to put the conclusions on more formal grounds. We

also identified structural causes for originally purely subjective impressions like the lack of a main stairway across floors. The layout variants proposed on the basis of the investigation show promising improvements in formal analysis, surely with the caveat of empirical testing being necessary in the future.

In the reanalysis of the behavioural data of the experienced and inexperienced participants we could show that a newly derived set of route-based measures captures important differences between experienced and inexperienced users. These could be tied to different strategies of the wayfinders. We see this result only as a starting point for further refinement, especially since the relatively small sample size may have obscured even more pronounced effects. We are currently experimenting with additional measures of route properties, taking the sequential order of segments into account, e.g. travelling along or against a gradient of integration or connectivity.

Note that we are using space syntax as a *post-hoc analytic tool* in this paper. Although the study presented here is a controlled experiment, it does not include a systematic variation of space syntax properties as independent variables. For our future work it will be crucial to actively vary the space syntax properties of wayfinding tasks and layout variants in order to test the value of space syntax as a *predictive theory* of human spatial behavior.

Space syntax has in the past been mostly used to account for aggregate data of larger groups of people, with an emphasis on traffic flows and traffic density, often on the urban level. Wayfinding research concentrates on data from individual users with known goals and highly controlled settings. We see great opportunity to further investigate the feasibility of connecting these two fields. It is very important for research into spatio-cognitive processes to achieve a sound description and understanding of environmental variables. The present paper – albeit clearly being a work in progress – shows some initial progress towards this long-term research goal.

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The Ingredients of an Exosomatic Cognitive Map: Isovists, Agents and Axial Lines?

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Abstract. There is some evidence that an axial map, as used in space syntax, may be related to an underlying cognitive map in humans. However, the axial map is derived strictly from the mathematical configuration of space rather than any property of people. Hence there is a question of how a person might have embedded such a map.
In this paper we report the results of several experiments which aim to improve the correlation between agent and pedestrian movement. We use a database of external occlusion points derived from isovists constructed throughout the system to provide a lookup table for agents to guide their movement. Since the table is external to the agents, we refer to the visual architecture as exosomatic. The results do improve on previous studies, but are still far from a good simulation of pedestrian movement.
However, there is a philosophically important outcome from the experiments. When the agents are tuned to best performance, their movement patterns correspond to the axial structure of the system. This can be shown to be a mathematical result of their movement strategy; that is, the manifestation of movement, or the 'memory' of an agent experiment, relates to the combination of the internal structure of the agent and its engagement with the environment in the form of an axial map.
There are two unresolved steps from the relationship between individual and environment to human cognition: one, it cannot be shown that people do actually use occlusion points for movement, and two, even if they were to, it cannot be shown that they would use the resultant axial structure for higher level navigation decisions. Nevertheless, our results do provide evidence for a link between the individual and the axial map through embodiment of an agent-environment system, and our theory provides a mechanism for a link between the embodied map and preconditions for cognitive structure, which may in turn provide a basis for the future research into the means by which space syntax may be related to spatial cognition.

1 Introduction

Space syntax [1] is the study of the relationship between space and society. One of the central tools of space syntax is the *axial map*. An axial map is an abstraction of the space between buildings (or rooms and corridors of a building) to straight lines drawn through it according to a formal algorithm [2, 3] (figure 1). It has

been discovered that graph measures of the resulting network of lines correlate with aggregate pedestrian movement, particularly at the urban scale [4, 5, 6]. However, the means by which the axial map translates movement at the level of the individual to a measure of a graph has not been fully explained. Therefore, the aim of this paper is to explore the nature of the axial map through its relationship to the individual. This does not carry us directly from individual to graph measure, but it does provide a link from an individual in continuous space to an axial, or at least, axial-like, structure. To achieve this aim, we employ agent-based models to simulate pedestrian movement, and look at various parameters that affect their movement, before returning to the aim of understanding the axial structure.

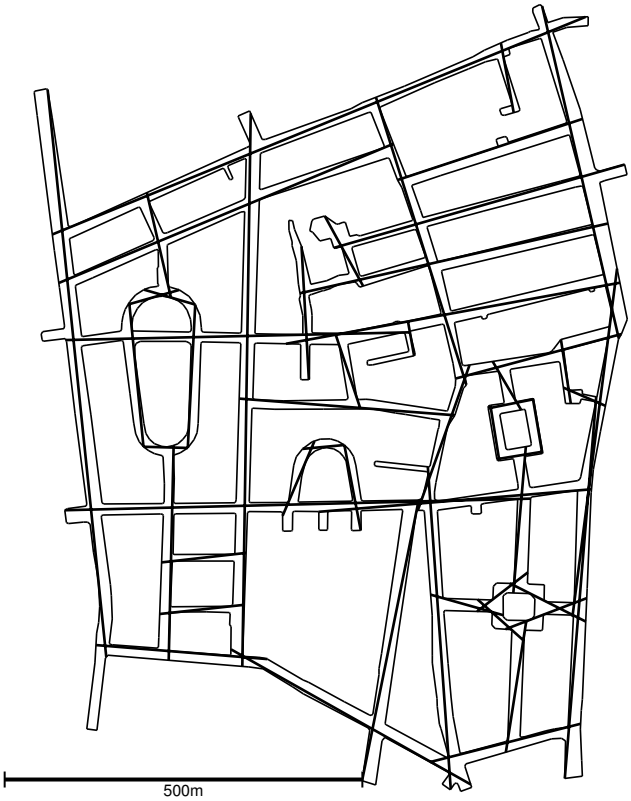

Fig. 1. An automatically generated axial map of Barnsbury in North London, within the open space of the area.

There is discussion about whether the movement correlation observed with axial maps relates to the internal structure of an individual, or whether it relates to the physcial constraints of the map.

Since the axial map definition derives from purely spatial constraints without reference to the occupants of a space it would seem natural to suggest that the overriding factor is the physical constraints of the space. The core premise is that placement of buildings or rooms leads directly to the movement observed. This is the theory of natural movement [5]. It is a theory that does not require an individual, rather the linkage is between society and space; the observed movement is the result of the aggregation of individuals, rather than any individual alone. It is this feature that allows the construction of a theory of the movement economy [7]: the spatial configuration self-perpetuates through the action of building shops in response to movement, which then leads to further movement, and further shops around it; that is, to Hillier, in his earlier work, the space is *the* 'machine', the mechanism in itself that leads to societal organisation.

However, there is another view, and that is that the axial line is a feature of the internal representation of space used by people[1]. It has been realised that the axial map is an extremely economic representation of space. Each line can cover many street segments, and requires, mathematically on a surface, just four variables (x, y location to x, y location or x, y location, direction and length). This economy, and the relation of axial lines to movement, has led to the suggestion that a cognitive map of the space might utilise similar features [8, 9]. This mirrors research in robotics by Kuipers that suggests that a skeletal framework just needs the notion of 'to the left of' or 'to the right of' in order to allow navigation from it [10]. Thus, Kim and Penn [11], investigate the relationship of axial maps to sketch maps as drawn by people. They find parallels between the graph importance of certain axial lines and the regularity with which the line is included in the sketch map. There is also a move to tie plausible cognitive functions to measures of the axial lines. For example, Dalton [12] has introduced angular analyses of axial maps in order to move towards experimental evidence of how people use minimal angular strategies to navigate from location to location [13]. The inclusion of these features has lead to improved correlation between measures and observed movement [14]. However, in all these studies, the existence of axial lines as a cognitive stucture on which to build the analyses is assumed. Thus, in this paper, we are interested in how the structure itself might arise, not through consideration of cognitive function, but through the engagement of agents with the environment.

In the next section, we will review the recent research in the direction of an embodied model of agent behaviour in the environment, including the relationship to active perception in robotics, situated cognition and further extensions to sensorimotor contingencies and phenomenology. We will then move on to practical experiments involving agent models, and show that there are deficiencies

[1] More evidence for this mode of interpretation exists than is presented here: in particular, the argument in the next section about eigenvectors can be used to show that if agents used strict natural vision, then movement could only be related to the connectivity of the axial line. As observed, movement is actually related to a second degree measure of each axial line, and thus must be due to some secondary effect: either people following people, or using memory in order to navigate.

in current models where large open spaces are concerned. Previous models have used first order, that is, direct, indicators of further configuration to guide their movement. In this paper, we apply a second order indicator, that of an occluding edge, so as to attempt to create a more 'human-like' pattern of movement from space to space. There is considerable experimentation to be done in this area, and we show the results of the application of several combinations of parameters to how the agents might respond to these environmental clues, both for the urban example of Barnsbury in North London (see figure 1), and the Tate Britain Gallery in London. It is discovered that the occlusion edge mechanism creates agents which correlate well with aggregate pedestrian movement in the urban environment. In addition, these agents create a pattern of lines through their movement, linking occlusion point to occlusion point. We show that these linkages reflect the mathematical mechanism used to create an axial map, and therefore that there is an innate association between the axial map and the embodied process of the agent movement in the environment. We suggest that this link provides evidence that an axial map is in fact the embodiment of movement in the environment, and thus inherently related to both the structure of the agent and the structure of the environment. However, we also demonstrate that this is not the whole story. We show that people in building environments *cannot* navigate by occlusion-edge alone if they are to produce the patterns of movement observed. There is a further connection with the environment not caught by these new agents, which is perhaps better caught by the original first order agents, or perhaps a feature of the environmental task not included in our models, such as, in the art gallery example used, a move to view paintings. Therefore, we are forced to conclude that axial models of building environments are also insufficient both representationally and practically. A rereading of the original space syntax literature relating to the Tate Britain Gallery shows that this restriction is implicitly acknowledged: the model used is *not* purely axial, but also includes convex areas (rooms), to equate movement to the model. The conclusion is that if a cognitive map represents the entire movement process, then it must be more complex than an axial map alone.

2 Background

An isovist is the visible polygon from a location in a plan of an urban or building environment, as shown in figure 2. Benedikt introduced the concept to architecture in order to try to quantify the perceptual experience of a place [15]. In particular, he recognised that the way people moved around a space might be influenced by the shape of the isovist, not simply by the objects within it. He supposed that people would be guided by isovist properties, following Gibson's suggestion that people may be guided by direct (or active) perception, that is, simply respond directly to the affordances offered by the environment rather than through any higher cognitive function [16].

Recently, with Penn, the author introduced simulation agents guided by the simple isovist property of visible area in the direction of movement [17]. We

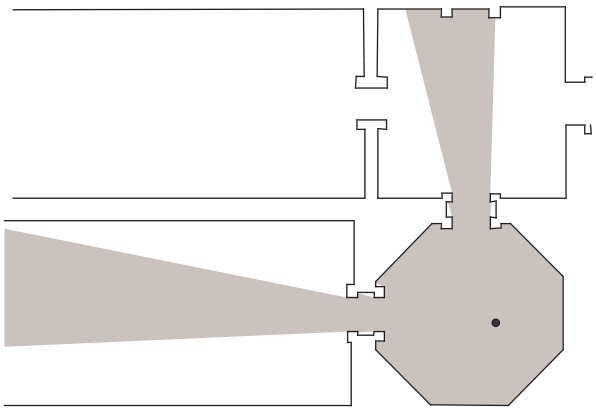

Fig. 2. An isovist generated from a location, or conversely, the isovist which converges on a location

constructed a dense grid visibility graph of a floorplan and allowed agents to choose their next destination from a selection of grid points in the agents' field of view. We discovered that if the agents are given a field of view of 170° and allowed to progress three steps before reselecting a destination, then aggregate movement of agents in a gallery space correlates well ($R^2 = 0.77$) with observed movement of people [18].

The power of this simple movement rule has led both Penn [9] and the author [19] to speculate as to the possible link between the agent movement and axial lines. Both of us point out that the information the agent sees is exosomatic: that is the agent samples the what Gibson calls the ambient optic array at any one location. The agent itself simply reacts to the environmental inputs at any time, producing a 'natural' outcome to stimuli. As such, the agents mimic those in Brook's subsumption architecture [20]. They have no explicit representation model, but the knowledge of the system (the natural outcome) is embedded in how the agents relate to a specific system. I have suggested that the system is essentially autopoietic [21] in nature: that there is an ongoing relationship between an organism and its environment [19]. Wheeler [22] calls such an ongoing relationship a 'hermeneutic dialogue'. He (Wheeler) suggests that this leads to a phenomenological understanding of the process; that is, that the experience of the agent can be accessed at the metalevel of the dialogue between agent and (to the author) the environment. Penn's analysis [9] is more clearly related to the notion of distributed or situation cognition [23, 24]. That is, that the knowledge exists out there, in the environment, and the agent is the receptor of that knowledge. In both the cases of Penn and myself, however, there is a desire to suggest that the axial map has some sort of relationship to the agents – either the result of an externalised memory or as a physically embodied system – which is not directly internal. O'Keefe, who proposed that the hippocampus may act as

the cognitive map in humans [25], also points out that any brain structure must inherently relate to the physical structure, and that there is an essential intertwined relationship between representation and physical structure, be it in the brain or the environment [26]. It is an area that O'Keefe calls 'neurophilosophy' and it is echoed in the visual sensorimotor contigencies proposed by O'Regan and Noë [27]. In effect, O'Regan and Noë suggest that visual consciousness is only possible in relation to an environment and meaningless without it. The point is that there is a constant overlap between the representation in the brain and physical environment; where the information is stored is to a certain extent flexible, and features structural properties of both the environment and the individual. The emphasis herein is how structure might arise from movement and engagement with the environment.

At one level, Penn and my [17] agents are even more simple than we have already suggested. Since each agent only reacts to the information directly available to it at any one location, the probability of its next move at any time can be written as the initial distribution at each location (a vector for the inhabitants at each location) ω multipied by a Markov transition matrix, for example, M. That is $\omega_{t+1} = M\omega_t$. The probability of a move after two steps is given by multiplying the matrix together, $M \times M$ or M^2, and after n steps, M^n, so $\omega_{t+n} = M^n\omega_t$. An interesting property of the steady state of movement in the system is that $\omega_{t+1} = M\omega_t$. Thus, the steady state vector is simply an eigenvector of the matrix M. We might call the first eigenvector ω_0. It should be noted that $\omega_0 = M\omega_0 = M^\infty\omega_0$. That is, the steady state movement is simply an eigenvector of the standard transition matrix[2]. Now, the transition matrix for the agents is extremely complicated, but we can draw certain conclusions. Most importantly, that the matrix does not rely on the last direction chosen by an agent. That is, any directionality involved in the movement of the agents is inherent in the physical properties of the location at hand. This suggests that, so long is there is no direct or indirect feedback into the system (for example, agents that see other agents), the movement result is a local property that can be extracted from the environment. This is not as easy as it may sound given the matrix, and it is for the steady state limit, rather than agents walking a certain number of steps, but it does give a direct relationship between a property of the environment and the *internal* properties of the agent. Hence, although we cannot access the internal properties of a real agent (and we have failed to cater for learning) we can suggest that the static abstract output from an agent run is, to a certain degree, a manifestation of its internal structure. As we have discussed, both Penn and I independently suggested that the static abstract output we presented had a relationship to an axial structure. As I have suggested here, if this is the case, the axial structure is an inherent property of the internal structure of the agent and the external local properties of the environment when applied together. However, the earlier agents presented by Penn and myself have shortcomings which lead us to suggest that the properties they presented were

[2] This is a standard mathematical result, first raised with the author by Wagner [28]

not actually axial, although perhaps closely related. Herein, I show that with minor changes, those agents could embody axial structures.

3 Methodology

3.1 Practical Problems and Solutions

Application of Penn and Turner's agents [17] to larger scale spaces has proved less successful than our initial building scale experiments [18], perhaps due to a less controlled environment where entrance and exit are unconstrained, but also perhaps because the agents appear to congregate in larger spaces, as their direct perception leads then towards open areas. This can lead to a stark contrast between agents and observation where there is open space such as a park. For example, in the area of the South Bank in London by the London Eye, paths recorded for people followed through the space differ strongly from the patterns of agent movement, as shown in figure 3(a) and figure 3(b).

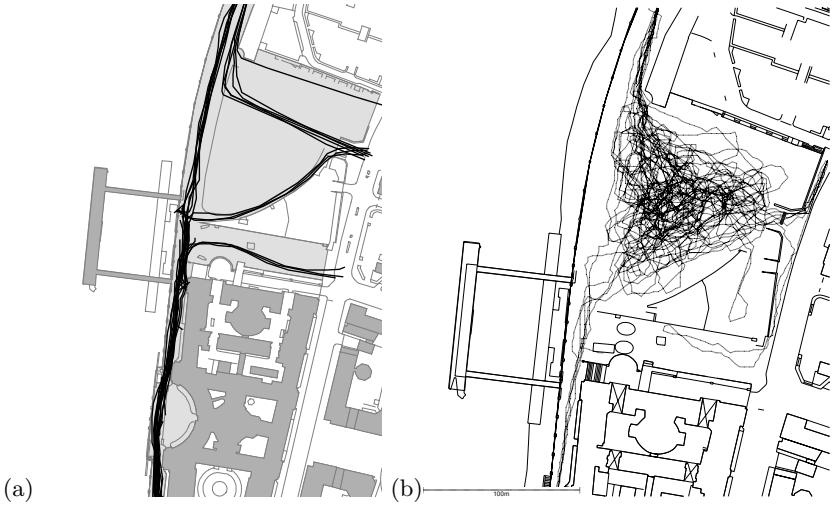

Fig. 3. (a) Pedestrian movement through the South Bank, London. Observations and image by Christian Beros, used with kind permission. (b) Trails of standard direct-perception agents in the same environment.

One might suggest that perhaps this 'milling' in the centre of the space is a simple outcome of the rules employed – if agents were to continue to their destination, rather than simply taking three steps before selecting another destination (see the beginning of the last section), then surely they would walk straight across open areas? However, there are two downsides to using this strategy: firstly, that experimentally this was found to be poor by Turner and Penn

[18], but also that the agents may still choose destinations in the middle of the space, and the people observed in figure 3(a) clearly are not. Their selection is to an edge, away from the central space.

We might also posit other possible mechanisms for movement based on the properties of locations. Conroy [13] has observed that people slow and appear to make direction decisions in locations where the isovist properties are skewed, that is, the centre of mass of the isovist and the location where the isovist was generated are separated. This implies that some property of the isovist is considered before making a movement decision. However, just because people are observed making decisions at locations with high skew does not mean that all locations with high skew result in movement decisions. Furthermore, it does not suggest *how* people move from area of high skew to another similar area.

Of course, a simple wall-following procedure may lead to the pedestrian movement patterns shown in figure 3(a) (and indeed we have presented results of animat experiments elsewhere that do evolve such a strategy [29]). However, whether or not people do actually simply follow walls when navigating environments is difficult to tell from observation data alone: roads typically have pavements at their edges, and town squares often have street furniture at their centres (particularly in the UK where our data is retrieved), and elsewhere avoidance of sunshine will play a role in how people cross open squares. Therefore the exact strategy used is difficult to ascertain, although further research in this area required.

In this paper, we will consider another possible mechanism to allow crossing open areas as shown in figure 3(a). When Benedikt introduced isovists, he also proposed a measure of *occlusivity*. This measure indicates where isovists have long lengths of occluding radials, that is, a radial that marks a boundary between visible and occluded objects (figure 4). For navigational purposes these occluding radials might also be important, as they mark areas of unexplored space that may be entered by continuing in the direction of the occluding radial. A rule that guides the agent according to the locations of the occluding radial or occlusion points should cause agents to take direct routes across space, as seen in the South Bank example. Therefore, in this paper we examine the effect of agents guided by occluding radials.

There are significant memory benefits from using occlusion points to guide behaviour. Once an occlusion point has been identified, it is relatively easy to track, as it marks a discontinuity between optic flow – as one walks more background comes into view, or recedes, whereas the point itself remains constant, even if it moves across the retina. Thus, it is simple to record locations of occlusion points and discard them if necessary.

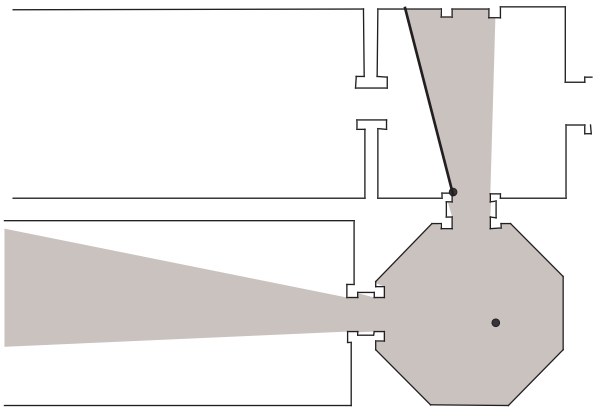

Fig. 4. An isovist showing an *occlusion point* (where the isovist meets an occluding edge), and an *occluding radial* (the portion of the isovist radial from the occluding point to its far end).

3.2 Implementation

For building environments, we construct a set of isovists covering a dense grid[3], placed every 0.75m throughout several test environments, as this gives an approximation to human step size. For urban environments, we follow [19], and use 3m grid spacing for ease of implementation. We break each isovist down into a series of 32 angular bins, and record the occluding radials in each bin. Simulation agents are then run in the system. Following [18], each agent has a field of view of 15 bins (about 170°), and moves for three steps[4] before making a new direction decision. As per [19] we simply transfer the 3-steps from building environment directly to the urban environment, regardless of scale implications.

Where we differ from our earlier agent models is that rather than selecting a point from the isovist to move towards, the agent chooses a direction based on the occluding points within its view. Several different approaches were attempted in order to try to understand how the occluding point movement decision could be best applied. In particular, there is question of resolution of the representation of the environment. If the resolution is too fine, then many occluding points occur at the edge of the system with every minor deviation. Therefore we ignore any occluding radial of length less than 1.5m (the occluding radial is considered just the open portion of the radial, as shown in figure 4). Obviously, a radial encountered at an oblique angle may still trigger the selection, but then this is probably reasonable: without further information, the agent is not to know

[3] The experiments in this paper were conducted using the Depthmap program, written by the author.

[4] In fact, this is actually implemented as a $\frac{1}{3}$ chance of changing direction in any one step, which does not equate to exactly a 'three-step' rule. It might better be conceived as a turn probability.

that this actually obscures a dead end. Once this simplification had been made, we then assayed several rules for choosing a new destination. In each case, the temporary destination was the occluding point itself. The experiments were as follows:

1. Control: standard direct perception agents as per [18].
2. Choose any occluding point at all from the available bins in the field of view.
3. For each bin in the field of view, choose the furthest occluding point, if any. Then choose any one of these at random.
4. For each group of 3 bins in the field of view (i.e., about 45° sections), choose the furthest occluding point, if any. Then choose any one of these at random.
5. For each group of 5 bins in the field of view (i.e., about 60° sections), choose the furthest occluding point, if any. Then choose any one of these at random.
6. For each bin in the field of view, choose the furthest occluding point, if any. Then choose one of these weighted according to how far away it is.
7. For each bin in the field of view, choose the furthest occluding point, if any. Then choose one of these weighted according to its angular deviation from the current course (the more, the higher the probability).
8. For each bin in the field of view, choose the furthest occluding point, if any. Then choose one of these weighted according to how far away it is multiplied by the angular deviation from the current course.

Experimental set up 1 was simply a control set up based on previous agent implmentations. Set up 2 was to test the affect of solely switching to occlusion points rather than any point within the system as a next step. Set up 3 was to try to cut down the number of occlusion points, so that directions with many occlusions did not bias directions with few, but important occlusions exist (for example to mitigate against situations where many columns exist). Experimental set ups 4 and 5 were to see if any advantage was obtained by simplifying the bin system further. Experiment 6 was used to try to influence the agents to follow better potential movement lines, rather than being distracted by elements close to the current location. Experiment 7 takes a different line to the same idea: rather than having the agent select a physically far location, to go for an angularly separated location. Finally, experimental set up 8 merely combines set ups 6 and 7.

4 Results and Discussion

For each experimental set up, a quantitative assessment was made against two test cases for which we have pedestrian data: a small model of an urban area (Barnsbury in North London, shown in figure 1) and a large public building space, the Tate Britain Gallery (see ahead to figure 7). For the Tate, agents were released from the entrance allowed to take 1800 steps in the system (as per [18]). Counts of the numbers of agents moving through the rooms of the gallery were then compared with data collected for people moving through the gallery

(obtained from [30]) for 54 rooms on the ground floor of the gallery. Similarly, for the area of Barnsbury, we compare aggregate gate counts of pedestrians for the whole day published by Penn and Dalton [31] with gate counts of agents at 106 gates. We apply a fairly arbitrary 1000 steps in the Barnsbury case, and release the agents from any location. In addition to these two quantitative experiments, we also looked at the qualitative output for the South Bank area, to see how the agents performed against the observed pattern when released from entrance points to the system (as the original observations of people were conducted). The quantitative results are shown in table 1, and the qualitative results in figure 5. Table 1 shows the linear regression R^2 correlation coefficient between the log of agent counts and the log of room or gate counts. The log is applied in order to distribute the data roughly according to a normal distribution.

Table 1. Correlation coefficients for agent versus observed movement for the Barnsbury and Tate Britain Gallery experiments.

Experiment	Barnsbury R^2 ($n = 106$)	Tate R^2 ($n = 54$)
1	0.55	0.76
2	0.60	0.59
3	0.42	0.55
4	0.24	0.45
5	0.28	0.51
6	0.47	0.57
7	0.67	0.60
8	0.68	0.34

From figure 5 it is apparent that none of the methods catch exactly the type of movement observed in people (refer back to figure 3(a)). In all cases, apart from perhaps experiment 8 (where occlusion point choice is weighted by distance and angle), the direct North to South path is lost. Even in experiment 8, the agents seem to decide to change direction directly across the open space, presumably due to the decision rule suddenly selecting a different direction after three steps. Certainly all do represent some improvement on the standard agent case. With the quantitative study the results are more mixed. Experiments 4 and 5 (where the bins are grouped) appear to do particularly badly relative to all the others. In all cases, there is a drop when the agents are placed in the Tate, with experiment 8 faring particularly badly, in contrast both to the qualitative results and Barnsbury, where it appears to fare best. Also doing well on Barnsbury is experiment 2 (a random choice of any occlusion point within the field of view). This is perhaps easy to explain, due to the fact that main streets will tend to have more intersections, and hence more occlusion points along their length, but the same explanation does not work with experiments 7 and 8, where angle of turn plays a role. It simply seems that these two experiments align better

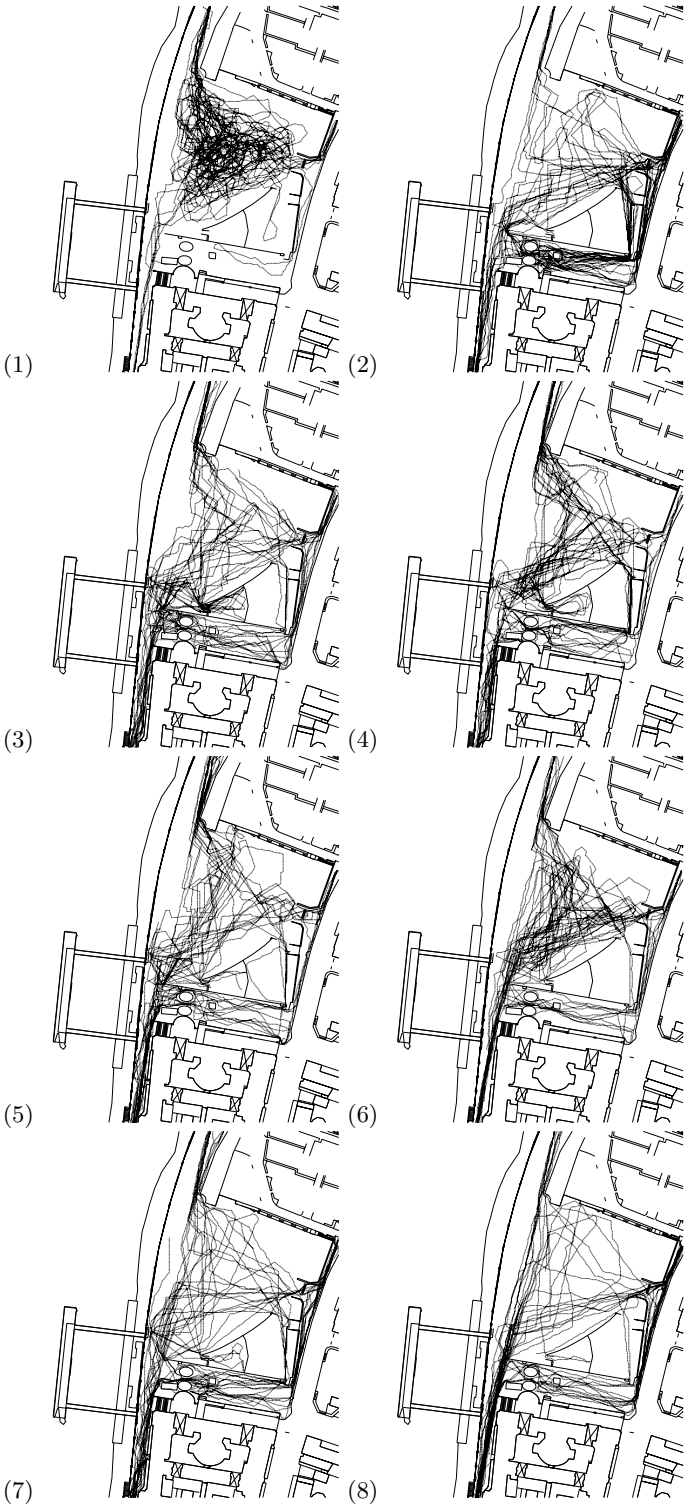

Fig. 5. Results from each of the 8 experimental set ups when applied to the South Bank area in London.

with the way people move through the system. They correlate with pedestrian movement considerably better than standard agents in Barnsbury, but worse in the Tate gallery; so what is going on? Figure 6 shows cummulative movement

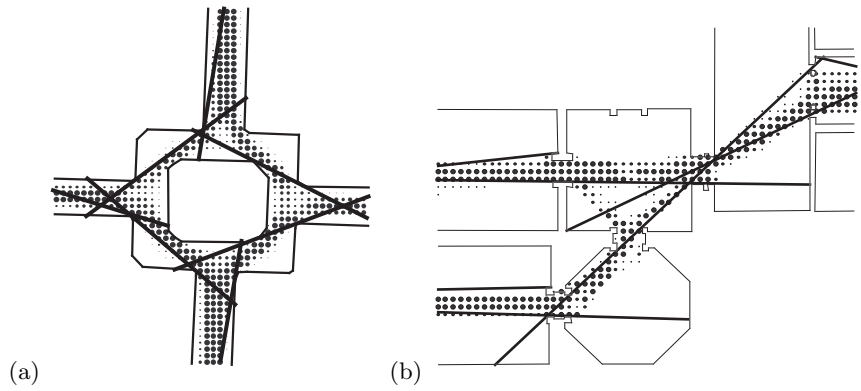

Fig. 6. Cummulative numbers of experiment 8 occlusion-driven agents (larger dots represent greater numbers of agents) overlaid on axial maps (bold lines) in (a) a section of Barnsbury and (b) part of the Tate Britain Gallery.

patterns of the experimental set up 8 agents as compared to the axial lines for the same areas. It appears that the movement of the agents aligns itself to a great degree with the axial lines. The same is true of the whole system, but difficult to appreciate without zooming into the detail. We should not be surprised that the agents do align with axial lines, as their movement is defined in a very similar way to the way in which axial lines are drawn. One of the rules for drawing axial lines is to join two reflex corners, and extend them. For the agents, reflex corners are occlusion points (corners around which the agents cannot immediately see). Therefore, if an agent moves by choosing one occlusion point, then moving to the next, and so on, then it is actually joining reflex corners akin to the axial map, regardless of the manner in which it chooses those occlusion points. The fact that the later methods depend on selecting the furthest occlusion point reinforces another of the byproducts of axial mapping: that longer lines are prioritised. So the situation leads to the agents sampling the axial lines of the system. In the Barnsbury case, this obviously leads to movement along the lines of actual pedestrians. However, in the Tate it appears to be flawed compared to the standard direct perception agents. We can show why this is the case with another pair of figures.

Figure 7 shows details of agent trails for previous agent implementations (figure 7(a)) and occlusion driven agents (figure 7(b)). It is obvious that the occlusion driven agents are drawn towards the top right-hand corner of the gallery. This is because there are more axial lines in the top right-hand corner.

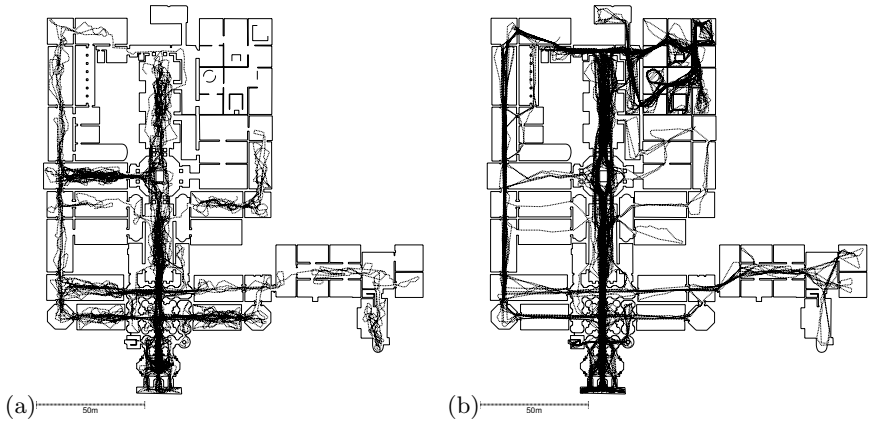

Fig. 7. Trails from (a) experiment 1 standard agents and (b) experiment 8 occlusion-driven agents in the Tate Britian Gallery.

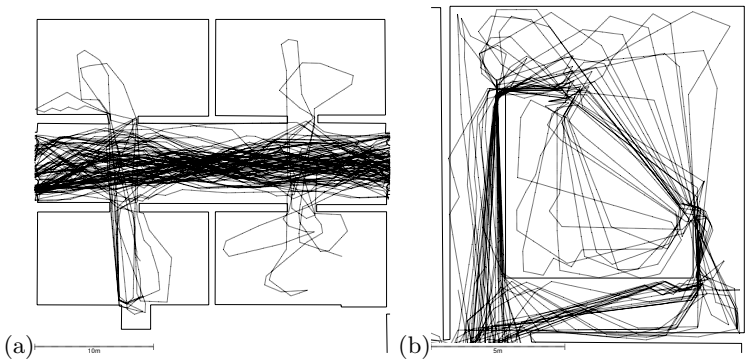

Fig. 8. Detail of trails from experiment 8 occlusion-driven agents in the Tate Gallery. (a) Rooms without internal configuration give no incentive to enter (note how a little extra configuration aids the room in the bottom left). (b) Rooms with internal configuration can over-incentivise entrance.

Figure 8 shows details of agent trails in two areas of the Tate gallery. The rooms in figure 8(a) are actually fairly well visited, but very few agents enter, precisely because there is no configuration within the rooms. The agents simply 'hover' at the entrances and leave, as the lack of further occlusion points provides no incentive to enter. It might be argued that allowing the agents to continue along the occluding radial may lead to their entering, in much the same way as axial lines are extended into spaces. However, this seems to lack the elegance of the occlusion point drive, and misses the point of why people may enter a room: if the room were truly empty then it is indeed likely that people would pass it by. We hypothesise that it is because these rooms have paintings they are entered. In any case, there is a second problem that cannot be extended by drawing axial lines. The room in figure 8(b), from the top right-hand corner, is barely entered in reality. However, the internal configuration of a temporary exhibition leads the agents into it (modelled with axial lines, the same would happen). This would probably correspond to the wishes of the exhibition designers, but in fact, the space (darkened to play film), attracts barely no-one. If these agents do so badly (in fact it is not 'so badly' for experimental set up 7, but comparatively badly), then how did the original space syntax analysis of the Tate Britain Gallery compare? The answer is, for a standard axial model, somewhat badly. In [30], the best model of pedestrian behaviour was in fact a combined model, that took axial lines but weighted them with convex spaces (essentially, the open room spaces). This is interesting, as the convex spaces, might be thought of as open space weights: exactly the attractors we were trying to exclude from the original first-order direct perception agents. It is no surprise then, that the original agents actually perform better than the occlusion-point driven agents in the Tate gallery. It also leads us to the conclusion that occlusion-driven is not the end of the story, and in fact, neither are axial lines. People may be behaving according to the axial structure of the city, but they are not behaving according to the axial structure of the building.

5 Conclusion

This paper has sketched out how agents may be programmed to use occlusion points to guide their movement. Qualitatively, we have shown that, in open areas, the paths generated by these agents correspond more closely to observed pedestrian movement than agents driven by direct perception, although there is still considerable room for improvement. Furthermore, quantitatively, the occlusion driven agents were shown to correlate well with observed movement in an urban system (up to $R^2 = 0.68$), but this was at the cost of previously found good correlation with movement of visitors to an art gallery space.

It was noted that the occluding points at the start of occluding radials are invariant as the agents move from location to location. These reflex vertices in the plan might be considered as the basis for a line map, joining the edges tranversed by the agents. Such a map has a very similar definition to an axial

map from the domain of space syntax [1]. Comparison of axial maps with the cummulative traces left by our agents show very similar patterns.

It was argued that the trails left by agents represent some externalised cognitive understanding of the system; in fact, with reference to O'Keefe [26] and O'Regan and Noë [27], it was claimed that cognitive understanding could only arise from the combination of the agent and the system. Further, the mathematical point was made that for any given movement rule, there is a direct mapping of the steady state movement pattern with the transition rules of agent movement. Therefore it was argued that internal property of the agent (the movement rule) is exhibited as a direct manifestation in the environment. The implication is that the cognitive function of the agent also relates to the environment in this way, and must then pick up elements from the movement-environment 'co-map' in order to direct its movement. In the occlusion point driven agent, the instransient features are the occlusion points themselves, that lead to the axial map. Therefore any further cognitive function of the agent ought to rely on a map isomorphic in some way to the axial map.

As we have said, this is not the whole story. The occlusion agents miss something of the function of human pedestrian agents. However, we suggested that extra features are just that: extra features where there is no configuration to drive the agents further. If this is the case, then the basis of cognitive movement may currently be lodged in the environment, as an exosomatic axial map.

6 Acknowledgements

With many thanks to Christian Beros for his permission to use the South Bank data presented in this paper. This paper expands on the short paper "Isovists, Occlusions and the Exosomatic Visual Architecture" to be presented at The Cognitive Approach to Modeling Environments Workshop, GIScience 2006.

The Depthmap program used for this paper can be obtained from Space Syntax Limited, and is free for academic use. Please see
`http://www.vr.ucl.ac.uk/depthmap` for details.

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Integrating space syntax in wayfinding analysis

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Abstract: This study investigates the relationship between space syntax and spatial cognition in the analysis of people's flows in a urban environment. More specifically, the aim is to analyze the influence of environmental features in wayfinding processes, considering jointly typical transport models parameters, such as distance (Wegener, 2004), and typical space syntax analysis parameters (Hillier and Hanson, 1984), as integration values. This contribution is a first research report about the development of a software for the study of the apparent divergence between those who (e.g. transport engineers), reckon that metrical distance is the main factor affecting a wayfinding process, and those who focalize the attention on the cognitive costs in choosing different routes, (e.g. the space syntax researchers).

Keywords: Space Syntax Analysis, Wayfinding behaviour.

The purpose of this work was to face the doubt recently posed by Steadman (2004 p.483) as an "important empirical question". For studying which strategies are used by people to navigate in urban environments: "Do we travel through shortest routes (in terms of metrical or temporal distance) as proposed by transport models, or do we choose the route characterized by the shortest number of axial lines and the highest level of integration?". As pointed out by Jiang e Claramunt (2002), one of the founding ideas of Space Syntax Theory derives by an attempt to understand how the spatial configuration of the environment influences the movements of the people inside it. More specifically, the integration measure indicates the level of integration of an environmental element in the immediate (local integration) and non-immediate urban context (global integration) (Jiang et al, 2000). Space Syntax's procedure is based on the representation and quantification of environmental characteristics of the built environment, with the aim to use them as independent variables for a statistical analysis of observed behavioral patterns (Penn, 2003) as routes and flows.
Space Syntax was recently compared from this theoretical and empirical point of view to Transport Models (Ratti, 2004; Hillier and Penn, 2004), though it was pointed out that these two models are based on different systems of environmental representation: As Steadman highlights, traditional *Transport Models* start from that *node-link* representation (Lynch, 1960) to attempt to preview traffic flows and different wayfinding behaviors inside cities and, more generally, in urban environments. In practice, these models detect the starting points and destinations, and calculate the shortest routes to connect them, in terms of time or distance. The hypothesis of these models is that people find out the shortest ways according to distance and time. These two measures could also not coincide, because of the effect of different parameters such as traffic and crowding. Starting from Steadman's doubt, the aim of this project

was that of analyzing the influence of environmental characteristics on wayfinding processes, in order to be able to approach strengths and weaknesses of both *transport models* and *space syntax analysis* in predicting choices about routes.

Method

Subjects

The subjects were 52 citizens of Cagliari (Sardinia - Italy), and ranged from 23 to 57 years of age (mean = 38,17 yrs). The sample was balanced by gender, since this was considered as a possible intervening variable (Lawton, 1994).

Materials

A tool useful to gather behavioral data analyzable with the considered models was developed. The goal was to create a tool that could allow us on one hand to perform several *ad hoc* analyses on a given urban setting while, on the other hand, keeping the maximum possible control of the experimental task. The software FINDyourWAY[1], was designed to simulate a wayfinding task in a real environment with a *route* perspective. The software was programmed in PHP language. The interface allows to navigate by pointing-and-clicking with the mouse, or by using mouse and keyboard together to move the point of view and select the desired direction. The subjects can therefore navigate from one node to another by clicking on a picture and watching the short movie of the navigation towards the subsequent node.
The neighbourhood (the ancient stronghold of the city) has been chosed for its clear boundaries and because it is usually explored by walking. This allowed us to eliminate the possible influence of traffic variables (lines, one ways, jams, speed limits, etc.). In this way, every street had the same theoretical chance to be followed. We realized a movie of every street segment in the neighborhood, in both ways (coming or leaving). We took a picture of every entrance, in all possible directions, for each node. All the photographs and the movies were shot in the same format, with the same quality, and in the same moment of the day. Movies and photos were then used to build the software reproducing completely the neighborhood.

Procedure

Subjects' task was to reach, starting from point "A", an arrival point "Z". There was not a single direct path connecting the chosen starting and arrival points. The task ended with an on-screen questionnaire collecting information about: personal data, neighborhood knowledge and the motivation for choosing the performed route (with an open-answer question). The subjects were completely free to choose personally

[1] FINDyourWAY is a software to simulate navigation in real environments developed by Renato Troffa and Ciro Auriemma (2006).

how to reach their destination: no instructions were given about choosing specific routes (e.g. fastest, usual, etc.). There was no time limit to complete the task: all the subjects took between 5 and 10 minutes to reach point "Z". The routes were tracked, as suggested by Golledge (1999), as a *trace of people's movements in the environment*. This trace was then measured by means of a geographical software.

Results

The data were analyzed from two different points of view: pedestrian traffic flow for each street and global routes chosen by the subjects.
In order to extract traffic flow information, we carried out an analysis of the local and global integration coefficients of the neighborhood, by means of the software Axwoman 2.0[2]. For each *axial line* we calculated the integration values, and we used this information to analyze the routes chosen by the subjects. Sixty out of sixty-nine neighborhood *axial lines* were navigated by the subjects. No correlation was found between the observed traffic flow for each street and its local integration value ($p>.05$), while a negative correlation was found between traffic flows and global integration values ($r = -.38$, $p<.005$). A log-linear analysis showed a significant association between high levels of global integration and low frequencies of choice ($z = 2.226$, $p <.01$) as between low levels of local integration and high frequency of choice ($z = 2.226$, $p <.01$).
The participants chose a total of 20 different paths to reach the destination. The routes were averagely km 0,707 long (min. km 0,551, max. km 0,977). The most chosen route (km 0,848) was followed by 15 subjects. No correlation was found between routes length and frequency of choice ($p>.05$). A log-linear analysis did not show any significant association between routes length and frequency of choice.
We have found significant differences in routes choice between men and women. ANOVA showed how the women choose significantly longer routes ($F_{(1,50)} = 7.817$ $p<.01$). A quantitative analysis of the open answers about the motivation for choosing a specific route showed a significant gender differences as well. The women cited significantly more aesthetical motivations ($p=<.01$). By means of textual analysis performed with the software SPAD-T, we isolated the prototypical motivations of *pleasantness* (0.655) and *panoramic features* (0.644). For men, the motivations were more often connected to the route *rapidity* (0.622) or *complexity* (.762).

Conclusions

The first thing to verify in this pre-test was if the software was able to represent effectively the setting used in our research. The software was indeed able to elicit different choices in the participants, who navigated from point "A" to point "Z" in

[2] Axwoman is a freeware program planed by Bing Jiang e Qingyuan Li for space syntax analysis of axial-line graph http://www.hig.se/t-inst/virtualrc/axwoman/

twenty different ways. The FINDyourWAY interface allowed for aimed navigation: all the people involved in the study were able to complete successfully the wayfinding task and to justify their choices. This result demonstrated that this software can be used effectively to gather wayfinding data in future studies. FINDyourWAY, thanks to its versatility, can be easily adapted to every built environment, simply by changing its structure and substituting pictures and movies. Our results invite to further analyze the syntax properties of the considered neighborhood. An interesting integration of the procedure used here could be to introduce different instructions manipulating the salience of *habit* and *route length*, along with a preliminary testing for cognitive space abilities. Moreover, other environmental elements should be taken into account, in order to enrich our design with more variables, as the presence of landmarks in selected routes (intended both as territorial markers and as significant places for the residents), capable of influencing the mental routes representation of the inhabitants (Nenci, 2000). From this standpoint, the initial question of our study represents the first step for an integrated research of wayfinding processes, where the Space Syntax technique contributes to the spatial dimension analysis of thw whole *Environmental Legibility*. This may help to study the construction of the cognitive representation of the environment, as the basis of orientation abilities and, therefore, of wayfinding performance.

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Wayfinding and navigation processes in Peraiki Coast, in the city of Piraeus or how the elements of an old city affect the spatial cognition of its users?

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Keywords: cognitive map, spatial cognition, space syntax, wayfinding, navigation

1. Literature Review

1.1. The city growth and the "palimpsest"

The city of Piraeus or Peiraeus has a history of many centuries and has, in fact, been inhabited since about 2,600 B.C. This fully informational through history environment is constructed in multidimensional terms. As each city is a "mosaic of social worlds" (R. Park, 1952, p.81), the behavioural settings (B. Lawson, 2001, p.23) comprise both the physical and the social environment. In this way, the urban environment of Piraeus could be characterised as a "*palimpsest*" of urban grids, a multi-layered record of streets, squares and passages that are being explored by the everyday walkers – both *inhabitants* and *visitors*. Everybody, while *walking in the City* read it "as a *text* but, crucially they also write it" *(*M. De Certeau, 1984, Ch VII). When people navigate through this "palimpsest", they create and simultaneously receive multiple cues that use for updating their spatial position and orientation.

1.2. Spatial cognition and wayfinding performance

Spatial cognition concerns "the study of knowledge and beliefs about spatial properties of objects and events in the world. Cognition is about knowledge: its acquisition, storage and retrieval, manipulation and use" (Montello, D. R. 2001, p.14771). Spatial knowledge changes over time, through processes of learning and development. The acquisition, the development and the application of knowledge establish different movement behaviour, and therefore discrete approach in a *wayfinding* task, i.e. in the act of traveling to a destination by a continuous, recursive process of making route-choices whilst evaluating previous spatial decisions against constant cognition of the environment." (Conroy-Dalton, 2001)

The *spatial syntax* of the environment consists of properties that include location, size, distance, direction, separation and connection, shape, pattern, and movement. Using the *spatial syntax*, people form their own "texts" of a place, *mental representations* and *cognitive maps* of the spaces whether from navigation or from

maps or from descriptions or from a combination, that allow them to arrive at their destinations and to give directions to others with some success. The *position of the subject*, and the distinction between *allocentric* (object to object) and *ego-centred* (body to object) (Klatzky, R. L. 1998) models of cognition is also a part of our research.

2. Methodology/ The Experiment in Peraiki Coast

This research suggests that the *three* different groups of people *Locals (the "inhabitants")*, the *Regional Locals* (the partially "*strangers*", those who live around Piraeus and they visit it frequently) and the *Visitors* (*pure "strangers"*, predominantly tourists), transmit, interpret and apply the cognitive knowledge in a different way, constructing distinctive cognitive maps that they use while they navigate in Peraiki Coast. Each group is using different kind of *spatial knowledge*, related to the degree of *familiarity* they already had with the place they were walking.

The experiment was conducted in the coastal zone of Peraiki, in the area indicated by the remains of the ancient Conon Walls (393 B.C.), thus allowing abundant visual information for perceiving parts of the ancient fortification system, but not for the rest of the city. The questionnaires were given to a sample of 85 people (31 locals, 27 regional locals, 27 visitors) during a weekday and a weekend. The questionnaires included a layout in which the zone was divided into 6 parts *(A, B, C, D, E and F)*, according to the geomorphology of the coast (Fig). Given a diagrammatic map of the coast, participants were instructed to *point the location they believe they were and the reasons of certainty*. They were also asked the frequency of visit and the degree of certainty of their answer.

The methodology included both *descriptive statistics* and *spatial analysis* based on *Space Syntax* Analytic Methods; the latter tools accurately describe properties of environments that we encode into our spatial knowledge and they explain the substantial proportion of the variance between aggregate human movement rates in different locations. Furthermore, space syntax tools analyse visual information (Visibility Graph Analysis–VGA, Turner et al., 2001) and describe it through the construction of visibility polygons, or *isovists*, from any given position within the configured space (Benedict 1979; Turner, Doxa, O'Sullivan &Penn 2001).

3. Findings

Comparing people's perceived location with their actual position, a high degree of deviation is highlighted. Locals' memory appears to be by far more precise than that of Regional Locals'. The latter group, although it uses knowledge, based on travel routines that connect ordered sequences of landmarks, and it is half –familiar with the Coast, it appears to give the least accurate answers to define their location, even in comparison to the Visitors that they visit the Coast for the first or second time. The results showed also that movement behaviour could be affected not only by visual cues, such as *Landmarks*, but also by environmental features such as the configuration of the coastline or the *distance* and *time* of *walking* estimation. Furthermore,

wayfinding performance is appeared to be aided by *maps*. To a considerable degree, the maps determine the extent of a subject's knowledge of its environment.

From this egocentric experiment, the results showed that there were some systematic errors (distortions) in participants' answers. A great amount of participants, that actually appeared to invoke the *Natural Environment* as indicator of their location, tended to confuse *certain* locations. The most frequent confusions were between locations *D and E*, *B and D*, *B and E* and *C and E*.

The division of the coast into 6 parts was made in order to analyse the *syntactical (configurational)* and the *geometrical* properties of Peraiki. The *axial map* is a method of representation of movement aggregation, composed of axial lines (fewest longest lines of sight and access) and it is a fundamental tool of space syntax (Hillier& Hanson, 1984). The results of the *Global Integration* values (measure that describes the average depth of a space to all other spaces in the system) explain the confusion between C and E and between B and D as the configurational similarities of the parts of the coastline entail error in the correct estimation of self-location. However, the confusion that is caused when people navigate in locations *D/E* and *B/E* could be investigated through the *geometric properties* of the Coast with VGA. Several interesting properties of the isovist (the polygon created by delineating the area visible to an observer in that position, most often assumed as having a 360-degree field of vision), like the *Isovist Area* (Fig.1) (how *much* of the environment is visible from any location) and *Maximum radial length* (a measure of the "longest available line of sight from an isovist's viewpoint", R. Conroy-Dalton, 2001, Ch. 8, p. 158) were taken into account in order to draw conclusions about the observed confusion in self-location.

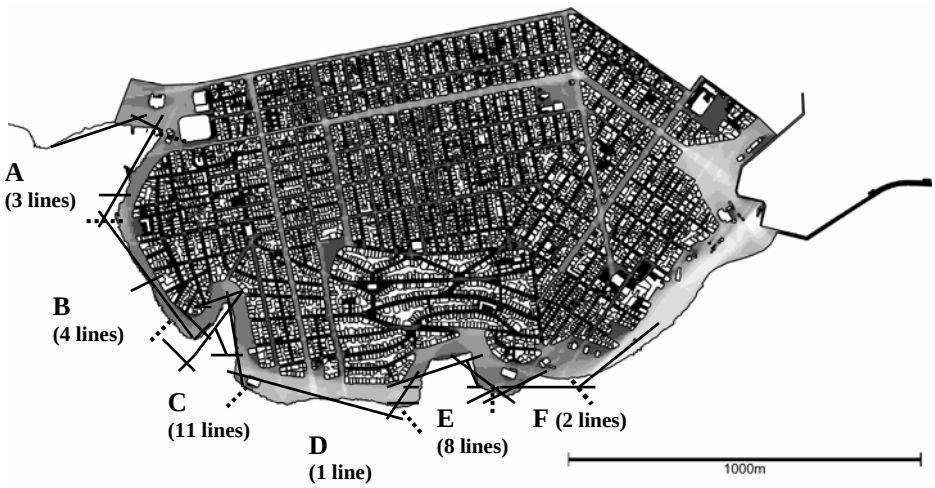

Fig.1 Map of the peninsula that shows a) the 6 parts that the coast was divided (A, B, C, D, E and F with dotted lines) b) the axial lines that consist of each part of the coast c) the measure of *Isovist Area* (VGA, where lighter colour denotes the maximum value and darker represents the minimum value of the measure).

4. Discussion

The findings from *Recognition Tasks* (Golledge, R. 1992) in the Coast showed that the relationship between *geometric measures* of isovists and *syntactic measures* of isovists (referring to the *overall structure* of the world), is highly significant. The fact that there are not strong correlations between certain geometric measures of isovists and syntactic measures (*connectivity*/*Maximum radial length and isovist area/visual integration*) implies the danger of error if we attempt to make global inferences from purely local information. This could probably explain the fact that the majority of subjects made wrong judgments about their position within *the whole system* based on visual information of the space that they are occupying. Local (visual) information appears to be critical to navigation along the coast; to a large extent the local surrounds provide an *azimuthial reference* (Loomis et al., 1999), i.e. information such as the location of the sea, the position of the sun, the position of the islands opposite the peninsula and the position of celestial bodies. However, no matter how crucial this information is, it was found to be misleading and confusing as the most of participants failed in a successful updating of their position.

The elements of the city of Piraeus affect movement behaviour in different ways, as the cognitive maps are internal representations, subjective structures that encode the spatial relations. This research was an attempt to correlate spatial configurations and cognition of the urban environment of Peraiki Coast so as to investigate the *knowledge* that urges human behaviour and shapes movement. And that *knowledge* is a combination of sensation, perception, belief, attitude, reasoning, intentionality, information processing, learning, image, affect, personality and language.

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The Role of Space in the Emergence of Conceived Urban Areas

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Abstract. A city is usually made up of numerous different named areas but how these areas are defined is problematic. Lynch (1961) suggests that the sense of urban areas are mainly determined by thematic continuities consisting of spatial characteristics, such as the width of street, building type, colour, texture, façade detail and so on, and also gives a hypothesis that the image of urban area could be gradually developed and conceived through the network of sequences, a sense of interconnectedness at any level or in any direction. Rossi (1984) also argues that urban areas, identified as the study areas in his book, can be defined or described by their location in the city, their imprint on the ground, their topographic limits and their physical appearance which he sees as representing a consistent mode of living, involving a whole historic process of urban growth and differentiation. Both suggest, in effect, that there might be objective correlates for concepts of name areas, but little research since has taken this idea further. Here we ask if studies of cities as spatial configurations, using the techniques of space syntax, might throw light on these questions. Are there perhaps correlates between named areas and configurational properties?

The paper first reviews syntactic methods applied in the past in defining different areas. Hillier (1987a, 1987b, 1989) suggested that the optimizing correlations between spatial configuration measured by integration and movement rates provided a powerful method for picking out sub-areas within a larger urban areas. Such kind of sub-areas within urban like district were named as “natural areas” whose structure can predict movement rates. Peponis (1989) also proposed a technique of decomposing towns into distinct sub-areas along the consecutive axial lines of the highest choice value that indexes how many of the most direct paths between all the possible pairs of other spaces go through a particular space. When the choice core, the line of the highest choice, bifurcates, the cutting lines go along the lines which could maximize the total choice value while minimize the number of the cutting lines. Then, Hillier (1996) developed another technique for identifying urban areas that the correlation between global integration and local integration at the scattergram can be used to identify urban parts: the steeper slope of the regression line of sub-area across the regression line for a whole city could imply this distinctive sub-area. Read (1999, 2001) argued that the structures of Dutch cities were generated more from the conscious planning and design than from the spontaneous process, and as a result Dutch cities split themselves into the two distinct layers of supergrid, a network of streets carrying the longer distance movement in the whole city, and local area, the catchment for local scale movement and neighborhood activities. Then, he proposed

two techniques to explain this biplex urban structure. One is the integration gradient map, picking out the streets with high integration values relative to other streets in proximity and then tracing streets of high integration gradient based on integration R3 or Rn through urban grid, as a way to highlight supergrid; the other is the area integration map, indicating the concentrations of high integration at the radius 3 through giving a line the average of local integration values of all the lines within a topological distance of two or three (or within a certain metric distance) from this line, as a way to distinguish areas. At the same time, he proved a good correlation between average local integration of areas and average activities within areas in Dutch cities. With Hillier, Raford (2005) further developed the technique of correlation contour map, the continuous correlation transition between integration and movement as the boundary of sub-area changing, to distinguish sub-areas in the fragmented urban context. All these techniques are for the most part based on spatial properties of the area itself, rather than the properties of the context, which prima facie seems likely to be a factor in how areas are defined.

Can the interfaces between spatial configurations at the consecutive scales define area structures in cities and then explain the process of their formations? Or, do urban areas of cities emerge from the process of the embeddedness of each space into its context? These questions could be approached in the context of the Hillier's centrality paradox that is that the more integrating the internal configuration of a convex form and then the more its most integrated internal zones is segregated from it external environment, that is called centrality paradox. He suggested that the urban transformation would be the sequence of the tension between internal and external integration in this way overcoming the centrality paradox (Hillier, 1996). Does it suggest that a named area as an object could be identified at the critical point where the lines constituting this area are least embedded into their external environment, while radius rising up?

Which syntactic variable could be used to indicate the process of embeddedness of urban space? The study starts by exploring the relation between node count Rk of an axial line/segment, that is the number of neigbouring lines/segments found k depth (or metric distance of k) away from that line/segment, and radius, in the cases of Central London, East London and Central Beijing, which could proximately show how an axial line in average is embedded into the surroundings. It might be suggested that mean node counts of an axial map or a named area selected from the map, such as Mayfair of London, could have an approximate power law relation with topological/metric radius within the certain radius ranges (Table1, 2, 3). This can be mapped in a log-log radius plot where a few inflexion points might be found to differentiate area structure in cities.

$$MeanNodeCount = K \times Radius^{a} \qquad (Radius \in (\alpha, \beta))$$

The exponent of a could indicate the average speed of all lines of a region topologically/metrically reaching the surrounding lines as radius rising up, and the constant K relates to mean connection of this region..

Table 1. Mean Node Counts & Topological Radius.

Region	Radius Range1	a1	Radius Range2	a2
London	1,2	2.12	2,14	3.04
East London	1,11	2.78	11,40	1.55
Beijing	1,2	2.03	2,12	3.17

Table 2. Mean Node Counts & Metric Radius.

Region	Radius Range	a
London	10-10000	1.701
East London	10-20000	1.809
Beijing	10-10000	1.750

Table3. Mean Node Counts of the Sub-area of East London & Topological Radius

Sub-area	Radius Range 1	a1	Radius Range 2	a2	Radius Range 3	a3	Radius Range 4	a4
Surry Dock (LuxuryH)	1,2	1.663	2,12	2.869	13,24	3.943		
Surry Dock (SocialH)	1,3	1.578	3,8	2.995	9,13	2.034	12,25	4.194
Beckton N	1,2	1.585	3,30	2.544				
Beckton W	1,2	1.700	3,30	2.657				
Beckton E	1,2	1.700	3,30	2.657				
Limehouse (SocialH)	1,2	1.585	2,21	3.032				
Poplar	1,2	1.700	2,22	2.909				
Canary Wharf	1,6	2.247	6,10	3.055	10,17	2.417	17,25	3.963
NE_Isledog (SocialH)	1,2	1.807	2,7	2.832	7,14	1.777	15,27	3.799
NW_Isledog (SocialH)	1,6	2.803	6,15	1.527	15,27	4.007		

A new technique is then proposed for exploring properties of the context. Each axial line is taken as the root of a graph, and the numbers of axial lines found with increasing radius from the root is calculated, and expressed as a rate of change and

denoted as embeddedness. This embeddedness value is then assigned to the original axial line and expressed through bands of colour.

$$Emd(k\_m) \sim Log(NC\_k \div NC\_m) \sim NC\_k \div NC\_m$$

Emd(k_m) denotes embeddedness, that is a rate of change of node count of a line/segment from radius k to radius m, and NC_k denotes node count of a line/segment at the radius k.

The results show strong areal effects, in that groups of neighbouring lines/segments tend to have similar colouring, and in many cases these suggest natural areas. However the areas defined vary with the rate of change at different radii, with larger areas being identified by large radii (Fig.1 & Fig.2). This technique is applied to the central areas of Beijing and London, and the results compared to known named areas. It further visually compares the area structure sketched in the Lynch's case study of Boston with the area structure generated from spatial configuration of Boston, as a possible first step towards a cognitive dimension.

Finally, it is suggested that what is being identified through this technique is not an area boundary in the normal sense, but what we might call a fuzzy boundary arising from the relation between the configurations of space within and outside the area. It further argues that the spatial definition of urban area could be more influenced by the external structure of the area, which might be called as exogenetic effect.

Fig.1. Area Structure of Central London Generated By Change Rate of Node Count at Topological Radius k

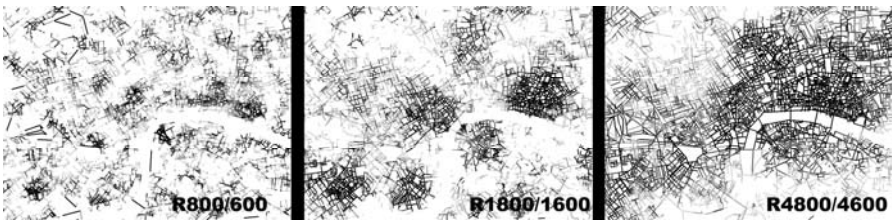

Fig.2. Area Structure of Central London Generated By Change Rate of Node Count at Metric Radius k