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SPATIAL NAVIGATION IN IMMERSIVE VIRTUAL ENVIRONMENTS

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To Sheep

Abstract

Pedestrian movement studies in real environments have shown consistent statistical relationships between 'configurational' properties of spatial layouts and movement flows, facilitating prediction of movement from designs. However, these studies are at an aggregate level and say nothing about how individuals make the micro-scale decisions producing these emergent regularities. They do not therefore 'explain' movement. Progress on this is difficult since decision-making mechanisms are hard to observe in the real world and the 'experimenter effect' is ever-present.

Could the study of movement in immersive virtual environments help? If it could be shown that movement in virtual environments was analogous to movement in real environments then micro-behaviour data (head movement, direction of gaze, visual search behaviours) could be obtained through virtual experiments. The aim of this thesis is to explore this possibility by constructing experimental worlds with spatial properties varied to reflect those known to relate to movement in the real world, and asking individuals navigate through them immersively.

Powerful analogies are initially demonstrated between virtual and real behaviour. Two types of micro-scale analysis are then performed: linear analysis, examining how routes are formed and how far linearity is conserved, using measurements of cumulative angular deviation along a path, string-matching algorithms to determine average routes, and analysis of isovist attributes along routes; and positional analysis, focussing upon pausing behaviour, including examining where subjects pause along routes, what choices are made at junctions, how isovist properties of pause-locations compare with an environment's overall isovist attribute distribution, and correlating pause-point and isovist data. In each analysis, 'subjective' movement behaviour is related to 'objective' properties of environments.

The experiments show results strongly suggesting how noted aggregate regularities are produced: linearity is strongly conserved, usually following long sight-lines, with pauses in configurationally 'integrated' locations offering strategic visual properties, long lines of sight, and large isovist areas.

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Chapter One:
Introduction – Goals of the Study

Architects, planners, geographers and other social scientists are currently unable to accurately predict pedestrian movement in the built environment. The need to make such predictions becomes particularly important when changes or interventions are being made to an existing urban environment. Equally, this knowledge gap can also be a problem when designing large, complex buildings (the larger or more complex a design problem is, the more probable it is that a designer's intuition will fail). In order to be able to make these kinds of predictions we need to strive to understand better how the built environment is *currently* being used by people. This is the approach that has been adopted by a body of work known as Space Syntax, an area of research that forms the foundation to this thesis.

Space Syntax Analytic Methods

Space Syntax is a family of theories and methodologies concerning the social use of space, which grew from the collaborative research of Hillier and Hanson at University College London in the mid-1970s. From the very beginning, Space Syntax research focussed on the relationship between space and social life, be this the social life of a simple building, a complex building (or set of buildings), a settlement or an urban district. At the time, the approach pioneered by Hillier and Hanson was unique, as it involved analysing solely the spaces between buildings as opposed to a building's (or buildings') geometric form (Hillier and Hanson 1984).

Through their research, it emerged that one vital component for the generation and maintenance of an environment's social life is pedestrian movement, since this type of movement (in contrast to, for example, vehicular movement) creates a potential for social interaction. This social interaction may be overt and direct (informal meetings around the photocopier in an office) or it may be indirect and discrete (the social policing of an urban area; personal safety afforded through the continual co-presence of strangers) (Hillier at al. 1992, Hillier 1996). Over the years, Space Syntax researchers have gradually come to the conclusion that pedestrian movement is one of the *best* indicators of the social success, or conversely the social failure, of an environment. This relationship between the environment and its inhabitants' through-movement lies at the heart of all Space Syntax research.

Gradually, researchers at UCL developed a series of new techniques for spatial analysis that can be used to *predict* pedestrian movement. Such prediction is possible due to the discovery of a statistically significant correlation between attributes of spatial configuration (of an environment) and pedestrian movement. One of the reasons why they were able to uncover this relationship stemmed from their focus upon space rather than geometric form. Space can be considered as not merely the 'gaps' left between buildings (or walls) but more importantly as *potential* for movement. If space is regarded in this way, then a strong and direct relationship between space and movement seems less surprising. However, over the years, one form of spatial analysis has proved to be consistently better at predicting pedestrian movement (and even vehicular movement) than all the others developed at UCL. This method of combined representation and analysis of space is termed ‘axial analysis’.

Axial analysis consists of an evaluation of the spatial structure of a system by examining the primary lines of sight (or ‘axial lines’) that pass through it. The first stage of the analysis is one of representation. It is necessary to fully represent the entire spatial structure of an environment by means of axial lines; this process is termed creating an ‘axial map’. The identification and recording of the longest and fewest lines of sight present (such that every space in the system has at least one line of sight passing through it) is a prerequisite of axial map production. Every line of sight will cross at least one another line (since only continuous systems can be analysed using Space Syntax), creating a network of axial lines that mutually intersect at intervals. It is this complex relationship of axial line intersections that forms the basis of the second stage of axial analysis.

In the second stage, each axial line is further represented as a node in a graph. When any two axial lines cross, this is indicated by a link between the two nodes representing those lines. Gradually a graph-based representation of the entire system can be constructed based upon nothing more than the intersection-relationship between axial lines. This graph is topological, containing no information about scale or distance. Once the graph representation has been built, the relative position of each axial line within the whole system can be assessed. This is achieved by calculating the number of steps in the graph (equivalent to real-world changes of direction) that it is necessary to follow, on average, to move from any line to all other lines in the system. Those axial lines that are, on average, a greater distance (in graph terms) from all other lines are said to be ‘segregated’ within the environment. Conversely, those lines that are only a short distance (in graph terms) from the rest of the system are termed ‘integrated’. The reciprocal of this value (which is known as mean step depth[1]) is known as the ‘integration value’ of an axial line and it is this value that has consistently correlated well with mean pedestrian movement flow data. It should be noted that currently the best indicator of pedestrian movement is the measure termed ‘radius 3 integration’. This measure is computed in an identical manner to the calculation for integration (as described above) except that it only considers lines that are three steps away. For this reason, it is also termed ‘local integration’. Therefore, at the core of Space Syntax research is the notion of relationship, and in particular the relationship between each space (whether is it represented by an axial line or another means of representation) and every other space in the environment under analysis.

As Space Syntax’s analytic methods have developed over the years, there has been an ongoing process of consistently checking all theoretical techniques against observed pedestrian movement patterns in the real world. This ever-increasing database of empirical data constitutes one of the largest collections of pedestrian movement observations and this empirical observation data has also served as an invaluable resource for this thesis. However, the majority of the observations in the database were taken at the level of people ‘en masse’ - cumulative, aggregate movement counts. Much of the data collected covers, for instance, the average flow of pedestrians along a street or road-segment and mean occupancy rates of rooms or spaces. Far fewer observations have taken place at the level of the individual. As a consequence of this, there currently exists a gulf of both data and knowledge between movement at the level of the individual and people's cumulative behaviour. It is not clearly understood which small-scale actions or decisions made by a person in an environment can result in the large-scale observations that form the Space Syntax database. However, does there exist a *need* to bridge this gap between large and small-scale movement? As Space Syntax analysis is *already* able to predict overall patterns of pedestrian movement should this not be sufficient for research purposes and the requirements of design professionals? Partly, this thesis is responding to the challenge that there exists a gap in current knowledge; the fact that the relationship between the individual and the population is so poorly comprehended is intrinsically an interesting research problem.

Pedestrian Movement and Emergent Phenomena

The fact that an enticing research area *can* be identified may be insufficient reason to undertake research; potential applications of the research should also be established. One reason to investigate how a person's actions may result in large-scale movement patterns is to understand better such cumulative behaviour. This is particularly necessary if overall pedestrian movement is considered to be an example of emergent phenomena. Can we even begin to categorise pedestrian movement as an emergent phenomenon if we have no knowledge of the micro-scale forces causing the large-scale movement?

For what reasons could pedestrian movement be regarded as an example of emergent phenomena? One, extremely clear definition of an emergent phenomenon is that it is an overall effect that stems from a small number of simple actions (or rules), *but* that the outcome *cannot* be easily predicted from the initial set of basic steps[2]. For example, using the above definition, patterns of axial line integration generated by Space Syntax analysis can *certainly* be regarded as an example of an emergent phenomenon. In this case, the 'set of simple rules' involves little more than determining whether any two axial lines are intersecting. The rule for generating the topological graph and then calculating the integration value of each line is also remarkably straightforward (refer to the earlier description in this chapter). However, the resultant pattern of integrated lines and segregated areas can be both surprising and revealing. It has even been known for quite experienced Space Syntax researchers to be unable to confidently predict the resultant integration pattern before performing the analysis. Since overall pedestrian movement mirrors the distribution of integration in an environment, it is extremely tempting to also describe this as an emergent phenomenon.

However, for movement patterns to be classed an emergent phenomenon, then it *should* be possible to determine the set of simple rules that give rise to these patterns. One example of where pedestrian movement can be seen to be an emergent phenomenon concerns the behaviour of tightly packed crowds. This type of behaviour is clearly demonstrated by the work of Benford et al. in (Benford, Greenhalgh et al. 1997). However, these results cannot be successfully scaled up to the urban level. It would appear that we behave quite differently when in a crowd situation, for at these times our actions are mostly governed by the movement of our neighbours. When moving through a city our behaviour is far less affected by the relative location of other people.

It is suggested that there may be a number of simple rules that give rise to natural movement in an urban environment. This premise formed the foundation of the paper (Mottram, Penn et al. 1999) in which programmable, software 'beings' (with vision) were given a set of simple instructions. Their instructions were to follow a long line of sight (with some minor random deviations) until a new, 'longer' line of sight is noticed and subsequently this new direction is followed. It was found that these rules gave rise to cumulative patterns of movement *suggestive* of real-world movement patterns. Given the tentative success of this earlier work, then it could be reasonably hoped that if a set of rules could be shown to give rise to overall movement, then this would provide the 'missing link' of Space Syntax research. It is not disputed by critics of Space Syntax that statistically significant correlations are found between observed pedestrian movement flows and patterns of integration; an explanation of the correlation is often sought and questioned. Why should we, as individuals, move in a manner consistent with the integration values of axial lines? This lack of a causal explanation has long been an 'Achilles' Heel' of Space Syntax research. So, not only would the establishment of a set of rules governing natural movement be able to confirm that urban-scale movement *is* an emergent phenomenon, but it could also begin to clarify why Space Syntax research is able to correlate pedestrian movement so strongly with space.

Observational Methods

If an identifiable need exists for such research, why has this need not been addressed before? Why, for example, have observations been predominantly made at the level of the population and not at the scale of the individual? If more observations had been made at individual levels, then our understanding of pedestrian movement as an emergent phenomenon might be more sophisticated than it currently is. At first, the focus upon cumulative movement patterns seems to be a curious imbalance, but in fact, there are a number of historical reasons why this has arisen.

Firstly, it is far easier to measure large-scale movement accurately. Minor, individual idiosyncrasies are 'smoothed' over a larger sample size, ensuring a consistently high statistical correlation (with spatial configuration). The act of making observations at the aggregate level is also far easier, since measures such as 'mean pedestrian flow per hour' rely purely on the accuracy of a quantitative record (how *many* people passed this point?)[3]. For movement observations where location data is necessary (such as directional movement flows), the relative inaccuracy of location estimates is often in keeping with the coarser resolution of spatial analyses of large-scale urban environments and therefore has never been perceived as a problem. In contrast to the relative ease of large-scale observation techniques, there are both technological and methodological problems associated with attempting to gather data at the level of the individual.

The various methods for observing individual movement can be categorised as manual (by direct observation) or automated (utilising technology to aid observation making). The family of methods that are used to manually observe individual pedestrian movement consists predominantly of the subject being discretely followed by an observer who marks the subject's route onto a plan. The subject need not be actually moving, as a variant of this method is used for making static observations (although in the case of static observations the location of multiple people will usually be noted on the plan). The first problem associated with this method of making observations is the inaccuracy inherent in the process of researchers transcribing subjects' locations onto a plan, since this relies on the researcher's *judgement* to estimate the subject's location relative to the environment. As this judgement is subjective then the result is clearly open to error. On the whole, up until now, this has not been an issue, since such fine-scale observations are rarely used, and as long as the *general* path taken by the subject though an environment is noted, this is usually sufficient for most research purposes.

Another problem associated with this method of data collection is a phenomenon termed the 'observer effect'. This occurs when the presence of the observer within the same environment as the subject affects the subject's behaviour. It is possible to attempt to avoid this through the discretion of the observer. However, even allowing for this, it is still extremely difficult to gauge the true effect of an observer's presence.

Finally, the last drawback associated with observing pedestrian movement manually, is the difficulty of recording sequences of different actions (taken by a subject). For example, it is certainly possible to follow, and to mark on a plan, a route taken by a subject. It could even be possible to approximately mark onto the plan any locations where that subject stopped or paused en route. It would be difficult, however, to try to accurately time the duration of their pauses, or note in which direction they are looking. It is not that it is *impossible* to perform this task manually, rather, it is the inherent difficulty in making multiple, simultaneous observations by hand.

Since there are a number of problems caused by making manual observations, one would think that it should be possible to make observations using mechanical or electronic means (i.e. to remove the observer from the process). Unfortunately, there are also problems associated with the automation of observing subjects in an environment. For example, although it is possible to use a video camera to initially record the movement (as in the Millennium Crowds Project, undertaken by Space Syntax Laboratory), computers are as yet unable to efficiently interpret this kind of data. The evaluation of this data still relies on an act of laborious (and potentially erroneous) manual interpretation. There are computer applications available that are capable of analysing video sequences, such as 'EthoVision' by Noldus Information Technology. EthoVision is a video tracking system that is capable of performing video tracking, track analysis and visualisation. However, this programme and similar applications usually rely on the location being observed being a 'closed system' (nobody leaving or entering the scene) coupled with prior identification of the objects (in this case persons) being tracked. This scenario rarely happens in buildings or urban environments. This software is better suited, therefore, to the tracking of rats in a maze.

It is possible to use a GPS[4] receiver to track people, in the way that Darken and Banker did in their paper (Darken and Banker 1998), in which they describe an orienteering experiment performed in a natural environment. They used GPS to record the subjects' paths as they traversed through the environment. However, even with current technology, the accuracy of satellite positioning can have an average margin of error of 13.2m in the United Kingdom[5]. In other words, this would probably be an even less accurate method of recording individual pedestrian movement than through making manual observations. Darken was only able to use this successfully as a method since he was investigating orienteering ability, and his subjects were traversing relatively large distances, in which an error of a few metres was negligible.

A popular and economical method of recording pedestrian flow is to use infrared beams coupled to electronic counters that are triggered whenever their beams have been interrupted. Examples of these are commonly used in many public buildings (such as museums and art galleries) to count visitors. Although this is accurate and (usually) unobtrusive, it is rare that enough of the devices are used to get an overall picture of movement. However, this method of recording movement is actually measuring the aggregate level movements, since it would be almost impossible to track an individual through such a system (unless they were alone in the building). In fact, the above method is actually measuring continuous pedestrian flow.

It is possible to accurately locate individuals within a building using an 'Active Badge' system. The Active Badge was conceived, designed and prototyped between 1989 and 1992 at AT&T Laboratories. An Active Badge is a small device worn by each inhabitant of the building, which transmits a unique infrared signal every ten seconds. The building is fitted with a series of sensors, which are designed to detect these transmissions and relay them back to a central database. The location of the badge (and hence its wearer) can be calculated using the information provided by these sensors. The largest single system that is currently in use is at the Cambridge University Computer Laboratory, where over two hundred badges and three hundred sensors are employed. Although it is possible to visualise this data graphically on a plan of the building, there has been no attempt to use this data to evaluate the building's performance or to relate it back to the environment in any way. However, this is a system that could be ideally used to track individuals through an environment. Perhaps in the future, when such a system is widely available and affordable, it will be used for such purposes.

One method that *can* be used to investigate individual movement utilises the nascent technology of virtual environments. Why might virtual environments provide the very key to understanding how the small-scale actions of people result in pedestrian movement? There are two primary advantages that such technologies bring to bear upon the problem of individual movement. Firstly, when using a virtual environment to 'observe' pedestrian actions, it *is* possible to make extremely high-resolution observations. Not only can the location of a subject in an environment be accurately measured (as well as the direction in which they are facing if the set-up is an immersive system), but the rate of measurement can be as frequent as every tenth of a second. In this way, every small step, hesitation, change of direction or brief glance can be recorded in the fullest of detail. The kinds of observations that it would be extremely valuable to make in the real world suddenly become possible to make in virtual worlds.

If observations can be made in this way, it is hypothesied that it *could* be possible to identify certain actions or behaviours, which, when repeated over the duration of an entire journey could be seen to produce a pattern consistent with either patterns of observed real-world movement or with patterns of integration (or both). It is suggested by this thesis that the key to gaining insight into this problem is empirical data and that virtual worlds can be used as a way to amass a large quantity of high quality empirical data.

Another advantage of using virtual environments can be seen by examining the concept of the 'scientific method'. One aspect of the scientific method concerns the procedure of conducting experiments. It is advised to attempt to reduce the number of variables present in an experiment, in order to properly observe the effect of the one variable being tested. Ideally, a researcher should strive to eliminate all extraneous variables (from the experiment) leaving only the *single* variable under scrutiny. In the case of real-world pedestrian movement, the number of variables that may be affecting or influencing route choice are too numerous to list. Not only are there too many real world stimuli to take into account but there may even be effects of the environment that we are, as yet, completely unable to identify.

Not only are real environments intrinsically complex, but there is an additional factor that serves to heighten the complexity of the problem, namely the effect of other people. Although, as stated previously, the presence of other people has a lesser effect on 'natural movement' than in a crowd scenario, this is not to say that the presence of others has *no* effect upon movement. One hypothesis[6] is that we are more inclined to select a well-populated route (which would result in a 'multiplier effect'). On the other hand, under certain situations (an ill-lit street at night, for example) certain people might be disinclined to walk along a street devoid of others.

In a virtual environment, there exists the advantage that the creator of the world (or the designer of the experiment) knows precisely what components went into the creation that world. A researcher using a virtual test-environment can be confident that the world will consist of only those factors that the researcher has chosen to include in the world. Therefore, the factors that might effect pedestrian movement in a virtual world are both finite and *potentially* knowable[7]. Variables being investigated (for their effect) can be examined by including or altering *only* those variables in the world. For example, it could be possible to create worlds that contain as little as space and form. It would be possible to test the effect of building appearance on movement by varying the textures incorporated into the world. The effects of street lighting or signage could be tested and even the presence of others. The presence of others could be generated by populating the world with avatars (people-like, programmed automata) to gauge any resultant change in movement. In essence, virtual environments constitute the ideal test-bed since the experimenter has complete control over the environment in a manner that is entirely impossible in the real world.

The advantages of using virtual worlds to gather empirical data can only exist if these results bear some relation to the real world. The fundamental question of this thesis is, therefore, whether we *can* learn from virtual environments about behaviour in the real world. Are real and virtual movement analogous in any meaningful or useful way? How far do human behaviours in simulated, virtual worlds reflect equivalent behaviours in the real world? If it could be established that it is possible to learn about real world behaviour from observing the actions of subjects navigating through virtual simulations, then this could serve to break open the observational-bottleneck currently impeding research in this area. With the ability to make a large number of observations over a wide variety of simulated worlds (each designed to specifically test one spatial variable) it could ultimately be possible to provide an answer to the question of how large-scale movement arises. From this answer, it should also be possible to authoritatively state why Space Syntax can be used as a predictor of movement (i.e. why there exists a positive correlation between pedestrian movement and patterns of axial integration).

Outline of Proposed Research

This thesis will begin by taking an environment for which the Space Syntax Laboratory's observational database contains high quality, meticulously observed movement data. The first stage of the experiment programme will be to reproduce these observations in a virtual world to determine whether the two (real and virtual) are, in any way, analogous. This process can begin to establish whether we can learn about real-world behaviour from the virtual.

This initial experiment may serve to highlight some of the technical and methodological challenges of this paper. One question that must initially be broached is to determine how easily virtual worlds can be used for this purpose and whether appropriate and relevant data *can* be gathered. An answer to this question must be found in the course of this thesis. For example, will a wide range of people *be able* to navigate through these worlds with ease? If such methods of generating data can only be used with subjects who are already sufficiently familiar with the technology, then the results will not represent an adequate population sample. The usability of the technology is, therefore, an issue that must be addressed early in this thesis.

The very design of the virtual worlds might also serve to be an interesting research challenge. For example, one question that may arise in the course of this thesis concerns the kinds of worlds that may be created and the limitations of the technology. The primary limitations of artificial environment construction are computer memory and processing power. In an immersive system, an over-large model (in memory terms) may produce problems for the subjects navigating through it[8]. However, it is a requirement of this thesis to discover and work within the capabilities and limitations of this technology. Although this is not a primary aim of this thesis it is, nevertheless, a factor that will be of relevance throughout its course. Answers to this question should be held to be a useful research outcome.

The next stage of this thesis will be to design a series of worlds that can be used to further investigate small-scale behaviours and actions made by people whilst navigating through them. The tasks that will be performed in these environments will be a series of wayfinding tasks in which all subjects start from one location and attempt to navigate to a pre-defined destination. By giving all subjects the same task, it is possible to discern any variance between individuals in a sample (and more importantly, any similarities). Whilst people are navigating through the virtual worlds any actions taken or decisions made en route will automatically be recorded. This data can then be compared to the spatial and visual characteristics of the different environments. A full and detailed description of the experiments' set-up and procedure will be given and the data so collected will be presented.

Once the empirical data has been gathered, the routes taken by the subjects may be investigated. The first technique that will be brought to bear on this problem is string matching. The section of the thesis that comprises string matching is semi-methodological as a new application of this technique is being introduced. This section will start to investigate how small-scale actions produce overall patterns of pedestrian movement by assuming a 'top-down' approach, namely by examining entire routes. The string matching analysis presented in this section will then be used to seek patterns in a sample of different routes. It is a new method for comparing a number of different routes and determining what patterns lie therein. The search for patterns is central to understanding movement as an emergent phenomenon, as it is the overall patterns that characterise it as such. At the end of this section, all empirical data will be analysed using this technique and hence may reveal any patterns in the data.

The next section of the thesis will also be semi-methodological, as it will introduce a novel method for analysing the 'straightness' of a route. Once again, this is a 'top-down' approach since this technique considers the characteristics of the route or path as a whole before considering what local rules might have given rise to such patterns. After analysing all of the route-data from the experiments, it is hoped that the outcome may contribute to answering the question of what kind of small-scale actions are important. At the end of this section, a solely methodological section will be introduced which will examine the changing field of view along a route. Although no substantive conclusions are drawn from this technique, it serves to introduce the notion that what we look at, or what information is visually available to us as we move through an environment may be critical to determining our actions. After considering the visual field along the routes, the thesis will then shift its focus. Instead of considering movement from a 'top-down' perspective (considering whole routes) it will employ a 'bottom-up' technique (actions that take place along a route). It is hoped that this duel-approach will combine into one method to investigate how the aggregate patterns of observed movement arise from a set of small-scale decisions.

The final section of this thesis will begin by considering whether there are any locations in the environment that correspond to specific actions of the subjects. The first method used for examining small-scale actions will investigate where people pause for significant amounts of time. The basic movement data will be analysed and every location where a subject pauses will be recorded. In a manner similar to the route string matching approach, a technique for identifying trends in the data will be applied which will aim to seek out any patterns in the spatial distribution of the pause points. Equally, in a manner similar to the examination of the visual field along a route, the direction of a subject's gaze at the pause points will also be recorded and visualised. This section is both methodological and substantive.

After considering where people pause, an attempt will be made to investigate whether these locations relate to any attributes of the worlds' spatial configuration. In order to investigate such a relationship, techniques of isovist analysis will be expanded. A method will be used that generates isovists in a grid filling all navigable space throughout the world. Finally, the attributes of the visual field at the pause points are compared to the overall visual field to determine whether people are more likely to pause in some locations as opposed to others. The findings of this chapter are essential to the understanding of how small-scale behaviours produce pedestrian movement.

It is hoped that this sequence of examining the small-scale actions outlined above may begin to provide an insight into some of the questions concerning the nature of pedestrian movement raised earlier in this chapter. However, before any empirical work can be undertaken, it is first necessary to review research that has already been conducted in the area of navigation and wayfinding. Wayfinding, as an area of academic research, is of the utmost relevance to this thesis since this is an area that has *started from* what is known (or is knowable) about movement at the level of the individual. In this way it can been regarded as a 'bottom-up' process of investigation as opposed to the 'top-down' approach taken by researchers in areas such as Space Syntax. Therefore, the following chapter (Chapter 2) will examine past and current research into wayfinding in both the real world and in virtual worlds.

Conclusions

The methodology being proposed in this thesis begins by establishing to what degree real and virtual movement are analogous. It will then continue by setting up a series of experiments, which will take place in different virtual worlds designed specifically to elicit a broad range of subject responses. Methods must then be developed for comparing the routes taken to other routes (to determine individual similarities and differences) and to a variety of spatial and visual environment-attributes. It is hoped that it may be possible to begin to understand, particularly through the comparison of small-scale individual actions to space, the simple rules that result in the emergent phenomenon which is pedestrian movement. It should also be possible to formulate a theory about why overall patterns of pedestrian movement correlate so well with axial line integration.

Key Questions

- Can we learn from virtual environments how people will behave in the real world?
- Do patterns of small-scale, individual actions exist that can be seen to accumulate, producing observed, aggregate patterns of pedestrian movement?
- Is pedestrian movement an emergent phenomenon?
- Can the study of individual pedestrian movement aid our understanding of the relationship between movement and spatial configuration?
- Are pedestrian movement in the real world and patterns of virtual world navigation analogous?

Notes

[1] This is known as 'status' in graph theory.

[2] Turkle defines an emergent phenomenon as "one whose components parts interact with sufficient intricacy that they cannot be predicted by standard linear equations; so many variables are at work in the system that its overall behavior can only be understood as an emergent consequence of the myriad behaviors embedded within." Source (Turkle 1997).

[3] For further details on observation methods see (Vaughan, Major et al. 1997).

[4] GPS is an acronym standing for 'Global Positioning Satellite'. This is a system whereby a user's location is determined by triangulating their distances from a number of satellites in stationary orbit.

[5] Source from the GNSS Flight Recorder Approval Committee.

[6] This hypothesis arose from observations made in (Conroy 1996) in which eye tracking experiments were performed, during which subjects were required to look at urban scenes. It was noted that where such scenes contained people, that these people were heavily scrutinised by all subjects in preference to all other environmental factors.

[7] Of course, there does exist the possibility that a factor, which is not expected to have an effect, may actually do so. In which case the creator of the virtual world may not even realise that is could be an effecting factor.

[8] One problem that may be caused is 'time lag'. This is when there is a noticeable difference between head movement and image refresh rates causing a 'lag'. This effect is also thought to be a contributing factor to 'VR sickness'.

Chapter Two:
Wayfinding in the Real and Virtual World

Abstract

This chapter will focus upon the body of literature concerned with wayfinding in the real world and will review recent research undertaken into wayfinding in the virtual world. It will begin by discussing a selection of definitions of wayfinding including an examination of the origins of the word. Through this survey of definitions, this chapter will gradually distil a working definition of wayfinding to be used throughout this thesis. Next, in reviewing wayfinding in the real world, different methods of assessing wayfinding performance are presented and assessed. Wayfinding papers that focus upon the effect of the environment on wayfinding performance are then reviewed and their methods discussed. After identifying problems with both these aspects of wayfinding research (the assessment of behaviour and effect of environment), this chapter goes on to examine more recent work. This work investigates wayfinding performance in the virtual world, and asks whether virtual environments are considered adequate research tools to investigate this phenomenon. Papers highlighting issues of research methodology are reviewed, with particular attention paid to papers seeking to establish whether interface and/or procedure have any effect on resultant data. A series of wayfinding experiments conducted solely in a virtual environment are then discussed, highlighting factors that lead to a series of papers that investigate the effect of Lynch-inspired environmental components (landmarks, paths, edges, nodes and districts) upon wayfinding. Finally, a number of papers attempting to compare real and virtual wayfinding behaviour are compared, leading to the conclusion that, broadly speaking, the same approach is taken by all the researchers reviewed. Rather than wayfinding behaviour, it is resultant spatial knowledge that is being analysed. Assumptions of equivalence (that real wayfinding correlates to virtual wayfinding) are made based solely on this. This chapter concludes with an observation that more objective methods of measuring wayfinding performance are needed, coupled with better analyses of environments, and that the degree to which real and virtual wayfinding performance are analogous still needs to be established.

Introduction

The focus of this Chapter will be the examination of the body of knowledge of wayfinding, both in the real world and, from recent years, in the virtual realm. If the research question underpinning this thesis is whether it is possible to *learn* from the study of virtual environments *how* people will behave in real environments, then it is vital to first understand what is *already* known about behaviour in real environments. In particular, the type of real-world behaviour of greatest relevance to this thesis is the act of what has come to be termed 'wayfinding'.

What is Wayfinding?

Arthur and Passini, in (Arthur and Passini 1992) attribute the term 'way-finding[1]' to Lynch, stating that its first occurrence was used in the book, The Image of the City (Lynch 1960). However, they estimate that it did not come into widespread use until the late 1970s, when it essentially replaced the phrase 'spatial orientation', hitherto used in academic writing. They attempted to seek some derivation and hence justification for the term wayfinding by examining its etymology, assuming it to be a derivation of the words wayfarer and wayfaring. Both of these words are derived from Old English[2]; wayfaring (archaic) was first recorded as being used in 1536 AD, whereas an older version of the word, wayfering (obsolete) can be traced back to 890 AD[3]. The definitions of these words mean journeying or travelling, particularly on foot.

Another term that may have some bearing on the phrase wayfinding is the term pathfinder. Pathfinder is a word of North American origins (although similar in sound and meaning to the modern German word, pfadfinder), whose usage can be traced back to the middle of the Nineteenth Century, indicating a person who discovers a path or way; an explorer. The origin of this word has been attributed to the author James Fenimore Cooper, as it formed the title of his book, "The Pathfinder", published in 1840, a term that was subsequently taken up by the English[4]. If the words pathfinder and wayfarer were to be combined, then the resultant term *wayfinder* could be held to be an obvious hybrid of the two parent words (its derivations partly Old English, partly Modern American). If one were to attempt to blend the *definitions* of the two words in a similar manner, one could readily surmise that the term wayfinding should describe a process of *travelling on foot in an exploratory manner*. Lynch's modern coinage of the word has unfortunately yet to find its way into any of the dictionaries of modern usage (either English or American English) even though it has now been in existence for more than forty years and has been used in the title of at least two books (Arthur and Passini 1992; Passini 1992).

If wayfinding is a relatively new word with scarcely any historical precedence, to what does it refer, and have any commonly agreed definitions, been established? At the very simplest end of the spectrum of definitions, as stated in (Carpenter 1989), "Wayfinding refers to what you do to find your way somewhere." However, this is perhaps a little too oversimplified and gives no indication of what it is that is actually being *done*, in order to find one's way. In (Arthur and Passini 1992) the concept of problem solving is introduced into a definition. They start with three distinct phrases that can be amalgamated into a single description; "Wayfinding is continuous, spatial problem solving under uncertainty." Although this definition begins to give some indication of what people do when they navigate from an origin to a destination, the act of "continuous, spatial problem solving under uncertainty" is still extremely broad and vague. For example, the act of playing the popular computer game, Tetris[5] would fall neatly into this definition. It is clear that a definition is required that implies not only the act of travelling from origin to destination plus the act of spatial problem solving (potentially including the *types* of problems to be solved) and encompasses a person's cognition of their environment.

If definitions of wayfinding that include the concept of environment-perception or cognition are now examined, it is necessary to initially return to Lynch, whose original definition of wayfinding was "a consistent use and organization of definite sensory cues from the external environment." In this definition Lynch stresses the importance of our senses to the act of wayfinding, yet omits to describe *how* it is that we use this information. In this respect, he is omitting the first two aspects of wayfinding mentioned in previous definition.

However, the primary importance of the input of our senses (our perception and cognition of the environment through which we navigate) is evident from the number of definitions of wayfinding which concentrate upon this aspect. For example, Gibson, in (Gibson 1979) stresses that " purposive locomotion such as homing, migrating, finding one's way [wayfinding], getting from place to place, and being orientated, depends on just the kind of sequential optical information [continuous visual perception of the environment] described." Although Gibson never states what wayfinding is, he is quite clear about what it is not. With regard to the theory of response chains and cognitive maps he says, "Wayfinding is surely not a sequence of turning responses conditioned to stimuli. But neither is it the consulting of an internal map of the maze" Although Gibson stresses the importance of perception and specifically visual perception to the act of wayfinding, he also concedes that there is more to wayfinding than purely responding to visual information in the environment. Namely, that although cognition and perception are essential to a definition of wayfinding, on their own they are insufficient.

If we wish to find an alternative example of a definition of wayfinding, which stems from a focus upon *only* the visual aspects of wayfinding, we come to a definition by Cutting, from (Cutting 1996), where he states that wayfinding is "how people find their way through cluttered environments with ease and without injury." This definition makes no reference to the acts of exploration or route finding. This is less than surprising since Cutting's research is into retinal optic flow. It becomes evident therefore, that the particular emphasis of various definitions can differ depending on the academic discipline of the author. For this reason it is suggested that an attempt to find or coin a single definition of wayfinding that is acceptable to a range of academic disciplines may be an impossible task.

In a manner similar to Gibson and Cutting, Golledge also emphasises the relationship between navigation and vision in his definition in (Golledge 1995), where he states that wayfinding "appears to be one of the primary functions of vision in virtually all biological systems. The processes involved includes cue or landmark recognition, turn angle estimation and reproduction, route link sequencing, network comprehension, frame of reference identification, route plotting strategies (e.g. dead reckoning, path integration, environmental simplification and en-route choice, shortcutting).” In this statement Golledge takes a rather unusual standpoint. He not only states that visual perception is *necessary* for wayfinding or navigation, he actually inverts this causal relationship and suggests that the necessity to move through our environment is one of the principal reasons for our sense of vision (i.e. we do not wayfind because we can see; we see so that we can wayfind.). In his definition he lists some of the processes he believes we perform whilst navigating, and although he does not mention spatial problem solving as a general term, many of the processes he describes can be regarded as spatial problem solving (others are clearly not, such as landmark recognition). In this way he begins to combine the acts of environment cognition and spatial problem solving into a single definition of wayfinding (albeit a task-list definition). This is a useful starting point for establishing what the ‘do’ of Carpenter’s definition (“Wayfinding refers to what you do to find your way somewhere.”) may really entail.

To continue this line of enquiry, it is possible to turn once again to Arthur and Passini in (Arthur and Passini 1992), where they state in another definition that wayfinding is “all the perceptual, cognitive, and decision-making processes necessary to find one’s way.” In this definition, Arthur and Passini, like Golledge above, are introducing cognitive and perceptual aspects of wayfinding into their definition, combined with a recognition of the necessity to make reference to the act of making decisions (spatial problem solving). Arthur and Passini eventually formulate a final definition of wayfinding, which they include in their glossary of wayfinding terms in (Arthur and Passini 1992). This definition states that wayfinding consists of “finding one’s way to a destination; spatial problem solving comprising three interdependent processes: decision making, decision executing, and information processing.” In this definition, they not only combine the act of travelling from origin to destination under uncertainty with the need for spatial problem solving, but in addition the perceptual and cognitive aspects are partially covered by the phrase “information processing”.

Before completing this section it is worth briefly noting a couple of recent definitions of wayfinding that are somewhat at odds with the majority of definitions noted in this Chapter. In (Darken, Allard et al. 1999) and (Bowman 1999) both authors refer to wayfinding as a term that describes solely the *cognitive processes* involved in finding one’s way from an origin to a destination. Darken, in the editor’s introduction to the above issue of the journal Presence (Darken, Allard et al. 1999), says, “We know that what we often refer to as *navigation* is not merely physical translation through a space, termed *locomotion* or *travel*, but that there is also a cognitive element, often referred to as *wayfinding*, that involves issues such as mental representations, route planning, and distance estimation.” Later in the same issue, Bowman makes the same distinction when he says, “We define *navigation* as the complete process of moving through an environment. Navigation has two parts: *wayfinding* (the cognitive decision-making process by which a movement is planned), and *travel* (the actual motion from the current location to the new location).” In both of these definitions, their use of the word navigation is far closer to other academic definitions of wayfinding, especially Passini’s. However such definitions appear not to be used elsewhere in other texts on wayfinding. One argument that could be used to counter against such a definition is that cognitive processes, considered in isolation of any movement through the environment, would be fundamentally meaningless, a standpoint first presented by Gibson. Therefore, since the act of travelling through an environment is a prerequisite component of our cognition of that environment, then the act of wayfinding must encompass both movement and cognition.

In order to arrive at a final, useable definition of wayfinding, it is necessary to consider briefly a selection of definitions that include a reference to spatial decision-making. In particular it may be useful to examine the relationship between environmental cognition and decision making. Passini says in (Passini 1992) that the "decision execution process based on a matching feedback mechanism in which expected environmental information… is matched with perceived information." This reference to a feedback mechanism has some similarities to a much earlier definition of wayfinding by Downs and Stea in (Downs and Stea 1973). In this book, they define wayfinding as comprising four stages. The first stage is that of orientation or the determination of both self-location and target-location (or estimated target-location) within the environment. The second stage is initial route choice, the selection of a route from starting location to target location. The third stage actually runs in parallel with a series of recursive instances of stages one and two. Stage three is route monitoring, constant checking of the route taken, modified by estimates of self-location and target-location (stage one) and reassessment or confirmation of route choice (stage two). The final stage of the process is the ability to recognise when the target has actually been reached. This can be summed up by the following diagram, in figure 2.1.

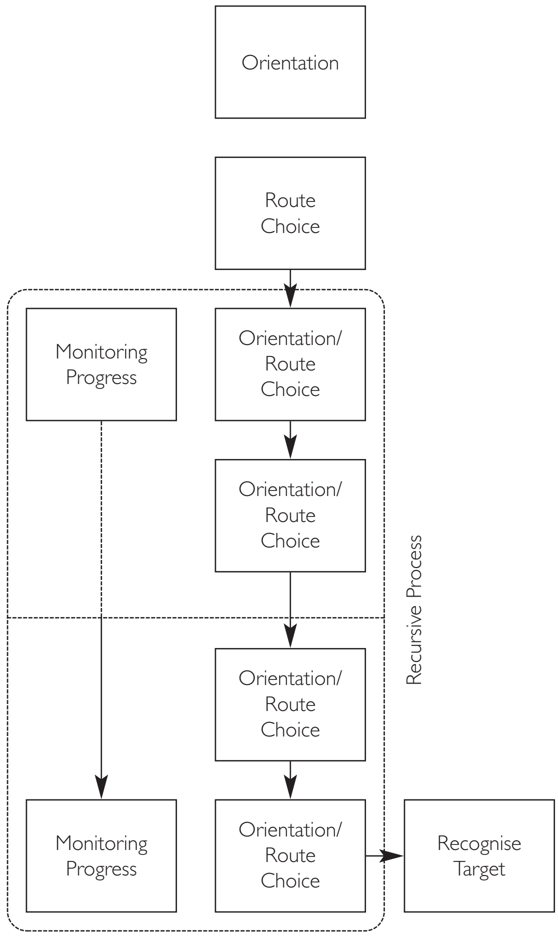


Figure 2.1 The Process of Wayfinding, After Downs and Stea

To summarise, the factor that appears to be essential to Downs and Stea's definition of wayfinding is a recursive act of measuring all decisions taken against continuous environmental cognition (monitoring progress). If this concept of recursive actions is taken into account, it can perhaps be used to coin a new definition of wayfinding, a definition that attempts to combine many of the components of other definitions surveyed in this chapter. One definition that could be thus created is that wayfinding is *the act of travelling to a destination by a continuous, recursive process of making route-choices whilst evaluating previous spatial decisions against constant cognition of the environment.* This is the definition of wayfinding to be used in this thesis. However, faced with such an all-encompassing and complex definition, it is probably worth being reminding ourselves that wayfinding is, in Raubal's words, "a basic activity that people do throughout their entire lives as they navigate from one place to another." (Raubal, Egenhofer et al. 1997).

Wayfinding in the Real World

In their paper (Raubal and Worboys 1999), Raubal and Worboys make another useful observation about wayfinding and the distinction between "knowledge in the head" and "knowledge in the world". These concepts originated from Norman in (Norman 1988). Norman makes these comments about the two kinds of knowledge, "Knowledge (or information) in the world and in the head are both essential in our daily functioning… Knowledge in the world acts as its own reminder. It can help us recover structures that we otherwise would forget. Knowledge in the head is efficient: no search and interpretation of the environment is required… Knowledge in the world is easier to learn, but often more difficult to use, And it relies heavily upon the continued physical presence of the information. Once the environment is changed then the information available is also changed. Performance relies on the physical presence of the task environment." He goes on to say, "Because you know that the information is available in the environment, the information you internally code in memory need be precise enough only to sustain the quality of behaviour you desire. This is one reason people can function well in their environment and still be unable to describe what they do. For example, a person can travel accurately through a city without being able to describe the route precisely."

If we consider these two types of knowledge in the context of the act of wayfinding, it is clear that the knowledge in the world is present in many forms and at many cognitive levels. At a lowest level of awareness, this knowledge can be regarded as being implicit in the overall configuration and structure of the environment, whereas at a higher level of awareness the knowledge in the world is explicit in the forms of, for example, signage. This range of 'knowledge in the world' (the range from implicit to explicit) can also be regarded as an example of non-discursive versus discursive environmental cues. One reason why subjects find it so difficult to describe the visual cues they use when wayfinding is that they only have words to name the explicit examples of knowledge in the world. It is relatively easy to determine whether a subject has attended to and/or acted upon information provided in the form of a sign (for example, we can ask them). It is difficult to identify a visual cue for which you have no concept or no name. As Peponis and Zimring say in (Peponis, Zimring et al. 1990), "the way that people verbalise or draw their understanding of the environment may be quite different from how they actually conceptualize it or navigate through it." Therefore, one of the difficulties inherent in examining the 'knowledge in the world', is that we can readily identify some visual cues, yet find it difficult to identify others. In contrast, in wayfinding terms, 'knowledge in the head' may be regarded as strategy, deliberate actions/decisions, and applications of past experience and memory.

Raubal and Worboys quite rightly level a criticism at wayfinding research, namely that all too often, research has focussed on the 'knowledge in the head' whilst ignoring the 'knowledge in the world'. Another way of phrasing this is that researchers into wayfinding have concentrated their efforts upon aspects of their subject's task performance in order to determine the effect of the world, rather than analysing the environments through which the subjects navigate. Rarely have both of these factors been examined equally. This is an interesting observation, since 'knowledge in the head' is patently the more impenetrable of the two areas of knowledge, as it is by far the more difficult to gauge. We are mostly able to assess 'knowledge in the head' by examining secondary sources of information only - what people *say* they did or are doing. It is almost impossible to examine primary sources of information, namely to examine what is *actually* happening in the brain whilst navigating. The closest attempt to do this is the work done by O'Keefe on hippocampal activity during wayfinding. A tertiary source of information is available by examining people's behaviour to see whether their actions shed any light on their 'knowledge in the head'.

However, despite Raubal and Worboys' criticism, it is possible to level a far more serious criticism at this body of research. Irrespective of whether 'knowledge in the head' or in the 'world' is being investigated, the majority of research in the field has suffered from a paucity of objective research methods. In order for work in this area to progress it is vital that researchers find more objective ways to analyse the 'knowledge in the head', i.e. the thoughts and actions of people in the environment. Moreover, it is necessary to seek more objective ways of analysing the environments themselves, so that we can determine which are the salient qualities of the environment that influence wayfinding performance. In order to begin to suggest ways in which research into the effect of these two phenomena can be furthered, it is necessary to examine research methods that have been used in the past. Some of the following papers focus upon knowledge in the head (both subjectively and occasionally objectively) and some focus upon knowledge in the world (again both subjectively and objectively).

This chapter section will start by examining how researchers in the field have attempted to investigate the role that 'knowledge in the head' plays in wayfinding. One approach taken to reach this goal is to analyse wayfinding performance. At the more subjective level, a common method is to ask the subject whether or not they found a wayfinding task easy or difficult. As Peponis et al. say in (Peponis, Zimring et al. 1990), "Direct observation of wayfinding is relatively rare, and even when it is attempted it is not always clear what is being recorded and how it might be analyzed." For example, although Braaksma and Cook in their paper, (Braaksma and Cook 1980), present an objective method for analysing an environment, their method for comparing this analysis to wayfinding performance is achieved by conducting informal interviews. They ask people to estimate the ease with which they found their way in the environment (in this case an airport).

Passini, in (Passini 1992), also uses post-test interview evaluations. In his case examples, he asked subjects to assess their own performance of the wayfinding tasks, as well as assessing the settings and the signage system (environmental factors). Asking people to gauge whether or not they feel an environment aids or hinders wayfinding, or to assess how well they judge that a wayfinding task was completed, is particularly problematic. These are the most subjective measures of all possible methods of assessing wayfinding performance.

Passini goes on to describe another method he uses to assess the performance of his subjects' wayfinding. This is a method that has subsequently been reproduced by a number of researchers, for example Raubal in (Raubal, Egenhofer et al. 1997), (Raubal and Egenhofer 1998) and (Raubal and Worboys 1999). Passini defines this method as eliciting "a wayfinding protocol", namely the "verbalization of the subject's problem-solving process while completing the wayfinding task." In effect, a researcher follows a subject, whilst that subject performs a wayfinding task. The subject's continuous, verbal commentary is recorded and later transcribed by the researcher. Passini describes the method used to prompt the subjects to verbalise their experiences. "The subjects were encouraged to describe freely what went through their minds at any time, to discuss the decisions they made, and to indicate what information they relied upon. The function of the investigator was to encourage this verbalization during the walk. The protocol contains an unedited version of the whole conversation pertinent to the topic as it was recorded on tape." Of course, the primary problem with this method, a problem that Passini was well aware of, was that the very presence of the interviewer, accompanying the subject through the environment, might have an effect on the performance of the subject.

Passini was particularly concerned about the researcher giving involuntary clues through their body language or facial expressions. He describes this problem thus, "After a short training period it did not appear difficult to follow a subject passively in his choice of walking directions, walking speed and so on, but it did prove difficult to refrain from behavioural reactions prompted by unexpected events."

The other problem with this method is a problem that Passini seems not to have considered, and is linked to the issue (touched upon earlier in this chapter) of identifying *what* knowledge in the world is important. For example, during this process, subjects are not only encouraged to describe what they are doing, and decisions they have made, for example, "That's not the direction I want to go". Subjects are also prompted to describe visual cues that they pick up, such as; "I see a sign that says I should go down that hall to go to gate A[6]". It is a relatively straightforward task to comment that an information-sign has been noted, but less easy to put into words the effect that, for example, the shape of the space being occupied has upon decision-making. Occasionally spatial attributes are reported, for example, "I come out in a big taller area[7]", "it's a long space", "a clear open area" and "The space is much narrower[8]" However, the vocabulary we have at our disposal to describe such phenomena is deficient. We do not have the requisite tools to describe precisely what aspect of the environment is of influence. In addition to this, there exists the additional danger that the subjects are merely putting into words, what they think the interviewer wants to hear, and hence the 'experimenter effect' comes into play. For these reasons, the method of asking subjects to give a running commentary ultimately remains an all too subjective and hence less than satisfactory method of investigation.

Another member of the family of 'self-evaluation' methods is the questionnaire used by Weisman in (Weisman 1981) to judge the extent of wayfinding problems in a set of ten different buildings. In this questionnaire, Weisman poses questions querying the number of times and degrees to which a subject has been 'lost' in the building and whether they would feel confident to give route directions to a stranger. This type of questionnaire is a popular method of self-assessment (and at least more directed than an informal interview). Nevertheless, Weisman, himself, recognises the problems inherent in this approach and at the end of his paper calls for the development of a set of more objective measures of wayfinding behaviour.

Towards the end of Weisman's questionnaire, the subject is asked to draw a diagram of the layout of the building. This method of assessing the knowledge of the building is taken directly from Lynch (Lynch 1960) and is referred to as a cognitive map. Lynch uses cognitive maps to determine the extent of a subject's knowledge of their environment. One problem with this approach was summed up succinctly by Passini and Arthur in (Arthur and Passini 1992), where they comment that, "The search for an answer [to the relevance of cognitive maps] was dampened by the observation that in many situations people got around quite well and did not feel disorientated even if they had only a very rudimentary understanding of the setting." In other words, there is no indication that an ability to draw a diagram of a building or environment necessarily has any bearing on wayfinding ability and vice versa. Finally, an additional problem with this method is how to begin to assess the qualities of a map so drawn. Gärling tries to explain this in (Gärling, Böök et al. 1986) when he says that there are doubts about "whether the results [of drawing cognitive maps] can be generalized" and that "problems of reliable scoring [assessing the results] are nevertheless likely to arise"

The criticisms cited above can also be levelled at another method of assessing wayfinding ability. An established method of assessing wayfinding ability is by using scene recognition tests, as described by Gärling in (Gärling, Böök et al. 1986). Once a wayfinding task has been completed, a subject is presented with a number of pictures or photographs of various scenes and asked to identify which of them had been encountered along their route. Again, a successful ability to perform this type of memory-recall test need not necessarily be indicative of an ability to have performed the original wayfinding task well.

Finally, a method that is also described by Gärling in the same paper is a particularly well known and popular method used extensively in wayfinding research. At various stages throughout a journey, participating subjects are instructed to point in the direction of salient locations or landmarks in the environment and/or to gauge their distance from the subject's location. The errors between the subject's estimations and their true orientation/distance are then calculated. The errors for all subjects in the test are then compared. This particular test has the advantage of being a more *objective* measure than the majority of those described so far. The relative objectivity of this technique has obviously contributed to its popularity as a research technique. However, this test essentially measures little more than a subject's estimation of their own position within an environment plus the relative position of other locations. Gärling comments that "The ability to localize reference points in the environment… [is] an important factor in the ability to maintain orientation." However, an ability to perform this task well is again not necessarily indicative of other abilities. Although clearly a useful measure in its own right, the question that must be asked is the same question that Passini raises with regard to cognitive maps. Namely, is this skill necessarily vital to the ability to find one's way through an environment or is it simply indicative of an innate ability to estimate orientations and distances? However, this method of assessing wayfinding ability leads to the next section of this chapter that reviews a group of alternative, more objective methods of measuring wayfinding ability.

The simplest objective measure for assessing wayfinding performance is to record the amount of time taken to reach the destination[9]. This was used, for example, by Butler in (Butler, Acquino et al. 1993), who timed subjects' journeys to the nearest second, up until the moment they reached their wayfinding goal. This method was also used by O'Neill, in (O'Neill 1991), where he measured three variables, one of which was the amount of time spent reaching the wayfinding goal. Another factor he measured was the number of instances of 'backtracking' (turning round and re-tracing part of a journey). Finally, O'Neill also assesses the number of wrong turns made at choice points (which he defines as "a turn in a direction that is incongruent with the most efficient completion of the wayfinding task."). O'Neill's estimation of wrong turns is similar to Peponis' calculation of 'redundancy' as a measure of wayfinding difficulty in (Peponis, Zimring et al. 1990). This is a measure of the number of choice nodes passed through in excess of the minimum number to get from origin to wayfinding goal. These kinds of measures contrast significantly with the more subjective measures described earlier in this chapter.

Finally, through an examination of objective measures of wayfinding ability, Golledge develops and uses most tests in his paper (Golledge 1995). In this paper he conducts a wayfinding experiment using thirty-two subjects in a familiar, real environment. The subjects were instructed to make their way from an origin to a specified destination and then back again. Their journey times were recorded whilst making a note of whether the subjects took the same route from their destination back to the origin again. He then asked each subject to gauge (in a questionnaire) why they had chosen the route that they taken (they chose from a list of criteria); he then compared their routes to a number of pre-computed routes (based on a sample of the same criteria). Some of the criteria he uses are "Shortest Distance", "Fewest Turns/ Many Turns", "Longest Leg First/Shortest Leg First". Although the act of asking the students to select which criteria *they* thought most influential is a quite subjective test, Golledge also scores their routes objectively against the set of calculated routes.

He notices that for one route, 62.9% of subjects took the same route to and from the specified locations, whereas for an alternative pairing of locations only 15.6% of subjects took the same route each time. He suggests that this difference can be reasonably explained through the use of strategies that minimise either distance or the number of turns; however he suggests that this cannot completely account for the asymmetry of routes. He states, "This implies that, in addition to the previously discovered asymmetry of distance perception… perceptions of the configuration of the environment itself (particularly different perspectives as one changes direction) may influence route choice. Thus a route that seems shorter or quicker or straighter from one end may not be so perceived from the other end, thus inducing a change of route." The conclusion of his work is that the main criteria influencing route choice decisions are shortest path, fewer numbers of turns and selection of longest-leg first. However, what is particularly interesting about this result is the fact that the direction of the route appeared to influence the route chosen. ('Shortest path' and 'fewest number of turns' are variables that are direction-independent, only 'longest leg first' can be affected by direction.) Explanations of this phenomenon do not support the theory that a cognitive map is crucial to path selection. Clearly the path selected was affected by a set of visual variables *dependant* upon direction of the routes (whereas cognitive maps are independent of direction). Two of the questions Golledge then highlights for future research are "For non-route retrace what were the criteria that caused a different route choice for the return trip? What difference does it make to predicting travel when one uses different route selection criteria for outbound and inbound trips?" Both of these are particularly provocative questions, suggesting potential areas of future research.

In the next section of this chapter, instead of considering the wayfinding performance of people, ways to assess the impact of the world are considered. These methods too, fall into two categories: ways of appraising the environment in a subjective manner, and techniques for analysing an environment objectively. Gärling suggests three methods of assessing environments. Firstly, he uses the subjects' judgements of the degree of differentiation of the environment (do different parts of an environment look different?). Then he gauges the visual access (visibility of key locations) of the space, and finally considers the complexity of its spatial layout (he has difficulty defining this measure). He proposes a system for classifying environments based upon these three criteria; however, the assessment of each criterion is relatively subjective and he fails to fully define how each of these criteria should be judged.

In a manner similar to Gärling, Weisman has a concept of how environments could be analysed, yet is unable to execute it in a truly objective manner. In (Weisman 1981), he particularly considers plan configuration. However, he ultimately assesses this by asking a group of subjects to rate a series of stylised plans against four criteria - preference, complexity/simplicity, 'describability' and judged ease of wayfinding. In other words, in failing to create a set of methods for assessing plan configuration, he seeks the subjective opinion of his subjects.

Butler et al. also use subjects to assess their routes subjectively in (Butler, Acquino et al. 1993). After conducting the experiments, their subjects were asked to rate a variety of routes, on a scale of zero to ten, ten being an "optimal" route and zero being a "terrible" route. In their results, shorter routes seemed preferable (when tested against 'number of turns' or 'number of decision points'). One factor that may have some bearing on his results is the fact that, particularly in his second experiment, the subjects were being asked to make judgements purely on the basis of examining plans of single routes through theoretical buildings. If subjects had actually to navigate through the routes, rather than simply examining at them on plan, would their assessment have been the same? Nevertheless, irrespective of whether it is a real building or a plan of a building being judged, it is still a highly subjective way of assessing the complexity of an environment. The fact that Gärling, Weisman and Butler all fall into the same trap indicates that an objective analysis of the complexity of environments is not an easy task.

Some people have begun to approach this problem in a more objective manner, for example O'Neill. In (O'Neill 1991), he devises a topological method for assessing the complexity of a building plan, using a graph-based analysis where each decision point is represented as a node in a graph. The degree of complexity is a relatively simple comparison of links to nodes (in effect calculating an overall link-to-node ratio). Although a good starting point, it does have one obvious flaw, which is that by simply looking at the average distribution of choices available, he fails to take into account any methods of analysing the visual properties of the environment.

Consider the following example. Figure 2.2 represents the corridor system within two buildings. The first building consists of two, long, parallel corridors linked at regular intervals by five cross-routes, typically forming a series of T-junctions. The second building is similar to the first, except that the rightmost corridor has been replaced by a series of shorter corridors, at varying angles to each other. Try conducting the following thought-experiment. Imagine a person standing in the bottom-rightmost corner of each building. In the first building this person would have an unobstructed view down the longest length of the building and would be able to note the locations of the adjoining side-corridors. A person standing in a similar location in the second building would have no such view, as the visual information available would be far more limited. It could be argued that the second building is more complex, and it is feasible that it could cause more wayfinding problems than the first building.

Using O'Neill's measure of complexity (based upon choice-point nodes and links), both buildings would be judged as equally complex. This is because they contain the same number of nodes and links. However, when axial analysis is used to represent the buildings, this type of analysis is based upon the fewest and longest lines of sight that pass through every space in a building. Because it uses sight lines, this representation picks up the fact that visibility in the second building is reduced. This factor is indicated through the overall mean depth of the building. In the first building, this measure is 1.53 and in the second building, it is 1.80. The increased depth (higher number) of the second building implies greater complexity. The comparison of O'Neill's measure and axial analysis is shown in Figure 2.2.

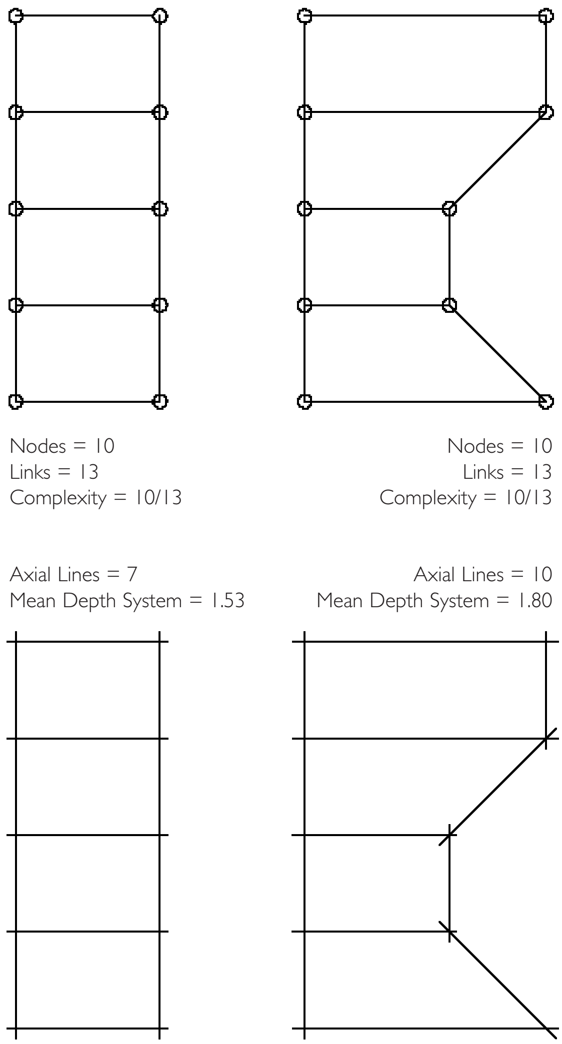


Figure 2.2 'Complexity' and Mean Depth of a System

O'Neill does, however, also make the point that, "other than these [papers by Braaksma and Peponis that he discusses] and a handful of other studies that attempt to objectively measure the environment, little research exists to relate the psychological and physical aspects of wayfinding to a larger conceptual model of legibility." Incidentally, although his method for assessing complexity was very simple, the results of his experiments were interesting. He reports that as the topological complexity of a plan increases, then the ease with which wayfinding tasks are performed decreases. It should be noted that O'Neill is one of the few authors who has attempted to use *both* an objective measure of an environment and an objective measure of subjects' wayfinding ability.

In the quote above, O'Neill mentions two other authors whose approach he admires, the first of which is Braaksma. Braaksma invented an ingenious way of analysing the complexity of an environment based upon the construction of a graph-based representation of a series of mutual visibility conditions. Braaksma's method starts by identifying a number of essential locations in an environment. In the example given in his paper, the environment being analysed is an airport, meaning that the types of location that Braaksma selects are, for example, the building entrance, check-in desks, passport control etc. He then constructs a large matrix, and tests to identify the locations that are visible from each of the other locations. He performs this test for each possible pairing of locations. Braaksma then goes on to develop a visibility index, which is a single measure of the overall, average visibility of key locations in the whole building. For example if everywhere were visible from everywhere else, this number would be 100%. The method he uses is very elegant, simple and effective. He goes on to report a relationship between this measure and perceived wayfinding ease. However, since the ease of wayfinding was judged extremely subjectively through informal interviews, this finding is not as significant as it might have been. Unfortunately, Braaksma has never continued this work.

Finally, the other person whom O'Neill cites positively in his paper is Peponis. In (Peponis, Zimring et al. 1990), they use a configurational method of analysing the building, based upon the longest and fewest lines of sight passing through every space in the building. They construct a graph-based representation of the relationships between these lines of sight (the crossing of any two lines is represented as a link in the graph; the lines themselves are the nodes). They then calculate how accessible any line is, on average, from all other lines in the system. The importance of the configurational properties of an environment to wayfinding is stressed by Passini in (Passini 1992), where he says that "Although the architecture and the spatial configuration of a building generate the wayfinding problems people have to solve, they are also a wayfinding support system in that they contain the information necessary to solve the problem." And "The comprehension of the principle by which spaces are organised appears as the single most important factor in facilitating image formation of a building [rendering it intelligible]."

After analysing the environment in this objective manner, Peponis et al. go on to observe and analyse the performance of the subjects as objectively as possible. The subjects are given wayfinding tasks with set pairs of origins and destinations. As the subjects find their way from an origin to a destination, they are followed by an observer who marks their route on a map. One of the primary measures of route analysis that Peponis then applies is 'redundancy' (mentioned earlier in this chapter). All in all, Peponis is one of the few academics who has conducted research into wayfinding and who has been able to consider *both* the environment and the performance of their subjects in an objective a manner as possible. It should therefore be of no surprise that this paper has been particularly influential in the field of wayfinding research.

If there is a criticism to be levelled at Peponis et al., it is due to the methods he uses to make the observations of the subjects' routes. In previous work done by Peponis and other Space Syntax researchers (see Chapter 1), the pedestrians being observed were completely unaware of their observation. This was easy to achieve because the kind of pedestrian movement being observed was what is termed 'natural movement', that is to say movement from everywhere to everywhere. In Peponis' experiments, due to the need for the experiments to be controlled wayfinding experiments with pre-determined origins and destinations, the observations could only be conducted using willing participants. These subjects would have been aware that they were being followed and that their movements were being recorded on plan. Although this was as objective as possible a method Peponis could have devised (at the time), there still exists a risk that the *presence* of the observers could have effected the subject's wayfinding performance. This risk reflects a limitation of the technology available at the time.

Wayfinding in Virtual Worlds

Today, if Peponis' wayfinding experiment were to be performed it would be possible to automatically track the paths of the subjects, without them being aware of the presence of an observer (akin to having an ever-present invisible observer). This could be achieved by using virtual environments to conduct a series of controlled experiments. Indeed, in recent years a number of researchers have attempted to work in this way, investigating how the use of virtual simulations may aid our understanding of wayfinding and navigation in unfamiliar environments. Such work dates back to the early 1990's whereas Peponis' paper, (Peponis, Zimring et al. 1990) was published in 1990, just as research using virtual environments began. At this point computers became powerful enough to simulate large-scale worlds and to allow people to walk through these worlds, or *wayfind* through them, in real-time. At the same time, hardware became affordable enough to permit such experiments. Since the early 1990's, the growth of papers on this topic has been exponential. During this decade, computing power has followed Moore's Law[10] (processing power doubling every eighteen months for the same cost), Therefore, the growth in papers on virtual wayfinding could be regarded as being fed by the accessibility of computing power. The growth in research on this topic is such that in April 1998, there was a special edition of the journal Presence devoted to Navigation and Wayfinding in Virtual Environments, followed by a second Special Edition on the topic in December 1999. It would be fair to say that it is a small but nonetheless flourishing subject area.

A number of academics entering this new research area originate from psychology or geography and many were previously involved in wayfinding research in the real world. However, this group of people have been joined by a substantial group of researchers who come from a computer science background. The origins of the range of researchers in this area mirror their concerns. Whilst many focus upon how wayfinding in virtual worlds may aid our understanding of wayfinding in the real world, others are beginning to see a necessity to understand the process of wayfinding and navigation in the virtual world, in order to design virtual worlds that are intelligible and easily traversed. This need becomes more crucial as the virtual worlds become more abstracted from the real world (for example in the case of three-dimensional visualisations of large datasets). As Darken says in his introduction to the 1999 special edition of the journal Presence, (Darken, Allard et al. 1999), "Few things are as fundamental to the human experience as the interaction between humans and their environment - be it physical or virtual." Later, in this same editorial, Darken and Allard go on to stress the dual nature of virtual wayfinding research by stating that, "In our attempt to make better interfaces for virtual environments, we must understand what carries over from the real world to the virtual world. On the other hand, in some cases, we want to go in the other direction: we want to carry skills or knowledge acquired in a virtual world to the real world." This duality of research aims and potential applications is also mirrored by Ruddle et al., in (Ruddle, Payne et al. 1998), when they say, "research should address the navigation of VEs per se as well as the transfer of spatial knowledge learned in VEs to the real world." The different goals prompting research in this area ensure a diverse focus of interest.

In order to begin to use virtual environments for wayfinding and navigational research it is first necessary to understand the technological limitations of the methodology. One issue that must be addressed early on in this body of research is to determine to what extent the technology *itself* may effect the outcome of the experiment. Only then can an answer be given to the question of whether we can learn from the study of virtual environments how people will behave in real environments. Some of the technological issues to be investigated include fundamental issues of interface design, such as those addressed by Ruddle et al. in (Ruddle, Randall et al. 1996). In this paper, they seek to determine whether there is a difference in patterns of movement between subjects navigating immersively and navigating non-immersively.

Ruddle compared the performance of subjects navigating through an immersive world, either immersively (using a head mounted display) or using a desktop (monitor) display. The virtual environments they navigated through consisted of two buildings containing an almost equal number of rooms. Whilst in the virtual worlds, the subjects performed direction and distance tests to gauge their spatial knowledge. One of the first (and in the context of this thesis potentially interesting) findings was that the subjects navigating using a headset could be seen to be taking advantage of this interface by looking around more than the 'desk-top subjects'. The ease with which this can be done immersively, in a way that feels quite 'natural', may explain this phenomenon. It was also found that the 'desk-top group' spent more of their time stationary than the immersive group. Nevertheless Ruddle also notes that contrary to his expectations, the proprioceptive feedback for the group using the headset did not drastically improve their orientation-judging abilities. On the whole, the conclusions of his paper were that similar patterns of movement were found between the immersive and non-immersive group.

Another important factor that plays a part in designing wayfinding experiments is the method by which motion is controlled through the environment. It is this issue that is addressed by (Peterson, Wells et al. 1998). In this paper they are primarily interested in determining whether navigational control devices that use whole body movements (and orientation) are superior to alternative control devices such as joysticks, which are independent of body position. In their experiment, the subjects were required to repeatedly follow a series of path markers; then the accuracy of their route learning was tested in the same environment without the markers. In addition to route-learning tasks, they were also required to perform some direction orientation tasks. It was initially found that navigational accuracy was higher using the joystick, and that route learning was equivalent for both devices. When it came to the spatial orientation tasks, it was found that there was a negligible difference in simple environments. However, the body-controlled devices were found superior as environments grew more complex. This is not to say that body-independent control devices inhibited their spatial cognition of the world, as found in (Bowman 1999), rather it appears that the performance of body-controlled devices is merely superior. Other work undertaken into interface issues which look into the effect of input devices include (MacDonald and Vince 1994; Wann and Rushton 1994; Slater, Usoh et al. 1995; Chance, Gaunet et al. 1998; Bakker 1999).

Another area for investigation is the effect of the restricted field of view (FOV) of most headsets. This was investigated by (Péruch, May et al. 1997) who performed a number of homing tests using headsets of differing fields of view (40°, 60° and 80°), finding no marked difference in performance between groups. They conclude that the amount of simultaneous environmental information is not a determiner of our comprehension of the environments. This is in contrast to an earlier paper by (Alfano and Michel 1990), in which Alfano and Michel found that restrictions in FOV affect the performance of certain tasks including the ability to follow a winding path, to perform a hand-eye co-ordination task and to form a mental representation of an environment. Note though, that since Ruddle found that subjects wearing headsets were more likely to move their head to a greater degree, it could be that we simply compensate for a restricted FOV by looking around more. Ruddle also cites earlier, unpublished work, in his paper, (Ruddle, Payne et al. 1998), where he notes that subjects occasionally travelled past locations just outside their FOV. However, he goes on to estimate that this behaviour accounted for no more than 5% of all navigational errors. In this paper, Ruddle also notes no difference between subjects' behaviour who are wearing headsets with different FOV (45° and 90°). Other work has been conducted into the importance of peripheral vision to motion perception, but clearly if virtual worlds are to be used for wayfinding research the precise effects of the various technical aspects of the experiment such as FOV need to be known and understood. This holds true for all other aspects of setting up experiments, whether they are desktop or immersive, and independent of the manner in which movement is controlled. In the context of this thesis, with regard to setting up any future experiments, the following guidelines can be applied. It is advisable, if using an immersive system, to have as wide a FOV as possible and to ensure that the physical orientation of the user contributes to their movement control (see Chapter 3).

Before continuing to look at the series of papers that describe various virtual wayfinding experiments, there is one other paper that is of relevance, which considers the methodological rather than the technical issues of setting up wayfinding experiments in virtual worlds. In the paper (Bowman 1999), Bowman considers how what he terms "travel techniques" can affect the spatial orientation of his experiment's subjects. The experiment was conducted in three travel 'modes'. In the first mode a subject follows a path chosen by the computer, with no control over their motion, yet they can look around whilst in motion (similar to being a passenger in a car). The second mode is similar to the first, the only difference being that the subject defines their own path before moving through the world; however once in motion they cannot deviate from their chosen path. In the final mode, the subject has complete control over their route choices during travel (analogous to being the driver of the car as opposed to the passenger in the first example). Bowman concludes, "For tasks in which spatial orientation is especially important, it appears that a travel technique giving users complete control over their position… can produce high performance levels [of spatial orientation]."

The result of Bowman's paper, suggesting that the best results occur when subjects are given greatest freedom of choice, leads to a series of papers which attempt to consider a number of different wayfinding issues in virtual environments. For example, one aspect of wayfinding that is far easier to investigate in virtual worlds (compared to the real world) is the combined effect of plan complexity and familiarity. Since virtual worlds can be fictitious (as opposed simulating real worlds), it is possible to generate a series of test environments of varying complexity. (The issue of how to begin to measure complexity was addressed earlier in this chapter; see the sections on O'Neill, Peponis and Braaksma). Since the worlds have no basis in reality, it is possible to *guarantee* that subjects cannot be familiar with them, and therefore *degrees* of familiarity can be strictly controlled. Two such papers that investigate this aspect of wayfinding are (Ruddle, Payne et al. 1998) and (O'Neill 1992). In O'Neill's paper, he examines the effect of plan complexity on wayfinding in simulated buildings. He finds that wayfinding performance decreases in proportion to an increase in environment complexity. However, as familiarity with an environment increases, the effect of plan-complexity is reduced. One explanation for this phenomenon is that perhaps we simply do not 'wayfind' in environments with which we are quite familiar. Therefore, a pre-requisite for the act of wayfinding should be that there is some degree of doubt regarding the correct route through an environment, and that once a route becomes well-known, wayfinding no longer takes place.

The most interesting research finding of this paper is evidence of an effect of plan complexity of spatial orientation. Environment complexity was measured using a definition developed in an earlier paper by O'Neill in (O'Neill 1991), using a measurement of the mean number of paths leading from a choice point in the world. O'Neill terms this measurement ICD or Interconnection Density (correct graph terminology would be 'mean node degree'). It was found that plan complexity (using O'Neill's definition) affected wayfinding ability; the more complex the building the longer it took to find the goal, and the more wrong turns were made by the subjects. By monitoring and comparing wayfinding performance against increased familiarity with the building, it was noted that the effects of plan complexity on wayfinding performance decreased with increased familiarity of the building. All of these experiments were undertaken in a simulated environment, based on the assumption that the results would be representative of performance in a real environment. In Ruddle's paper on the effects of familiarity, (Ruddle, Payne et al. 1998), his findings concurred with O'Neill's, namely that with increased familiarity of the virtual environment, subjects' wayfinding performance also increased. The means Ruddle and Payne use to assess wayfinding ability were: distance time to goal, and distance/orientation measures.

In Magliano's paper, (Magliano, Cohen et al. 1995), they consider the impact of the wayfinding goal on wayfinding performance. This experiment was conducted within a virtual simulation (in this case a simulation comprising a series of still images forming a walkthrough a small town). The extent of subjects' spatial-knowledge acquisition was measured after observing the pictorial walkthrough. Before the experiment, different instructions were given to subgroups of the participants. They were instructed to: either attend to possible landmarks, to the route itself, or to the spatial configuration of the small town. A control group were given no such instructions. Subjects' spatial knowledge was assessed by varying tests, which were applied to each group. Magliano et al. concluded that the subjects who had been given the instructions to learn only the landmarks did no better in the memory tasks than the route or configuration learning groups. The main distinction between the groups occurred during a direction-giving task. The subjects who had attended to either route or configurational information gave better (more accurate information) than either the control group or the landmark group.

This result suggests the relative unimportance of landmarks, leading to a set of papers, all of which use virtual environments to assess the impact of landmarks on wayfinding, with widely differing results. Lynch originally suggested that landmarks played a significant role in our cognition of the environment, in (Lynch 1960). Magliano's paper above seemed to suggest that for environment learning, landmarks had no effect upon a subject's spatial knowledge. This lack of evidence for any landmark effect is supported in the next two papers. The first of these is (Tlauka and Wilson 1994).

Tlauka reported upon an experiment in which subjects were required to learn their way through a sequential series of rooms (linked by two doors, one always 'locked' the other 'unlocked'), in a virtual simulated environment. For one group, memorable landmarks were placed in the environment to aid navigation by providing visual cues. For a second group, no such landmarks were present. No noticeable difference in task performance was found between the two groups. This unexpected result was explained by Tlauka and Wilson, in terms of strategy. They hypothesised that in the landmark case, room-landmark pairings were learnt, while in the non-landmark situation, sequences of right/left choices were memorised. They maintained that landmarks do contribute to navigation, but as only one of many navigational strategies used. They judged that the true effect of landmarks upon navigation can only be accounted for by sufficiently suppressing all other strategies or techniques. They then attempt to do this in an additional experiment (in which the R/L sequence-learning strategy is suppressed through the imposition of a simultaneous counting-backwards task). Again, there was no measurable effect of landmarks upon performance. Despite a result at odds with their expectations, they do, however, praise the utility of computer-simulated environments in the accurate testing of such navigational aids.

In Ruddle's paper (Ruddle, Payne et al. 1997), they investigate the effects of landmarks on route-learning ability and other spatial cognition tasks. They find a slight improvement in the time taken to complete the task in the environment containing landmarks in contrast to the environment without landmarks. However, when performing distance and orientation estimates, the effect of the inclusion of landmarks in the environment appears to be negligible. In contrast to this outcome that only weakly suggests that landmarks play any role in wayfinding, the subjects report in questionnaires that they actively used the landmarks, particularly in forming associations with specific locations in the world. The weak (as opposed to significant) effect of the landmarks appears to support the findings in Tlauka and Wilson and Magliano's papers.

In (Darken and Sibert 1993) and (Darken and Sibert 1996) the effects of landmarks on time taken to reach a wayfinding goal and on distance/orientation estimates were small. However, of all the differing navigational aids used in their experiments (landmarks being one such aid), some were of more use than others. Although it was not found that local landmarks significantly aided navigation, the inclusion of a virtual 'sun' as a global landmark did appear to improve performance. This distinction between local and global landmarks is subsequently addressed in a paper by Steck and Mallot (Steck and Mallot 2000), which provides the strongest evidence for the importance of landmarks to navigation.

Steck and Mallot's paper puts forward compelling evidence for the use of landmarks and describes a pair of particularly well-constructed experiments designed to investigate the dual effect of local and global landmarks. One of the techniques employed in this paper was to alter the relationship between the local and global landmarks, after the subjects had already navigated once through the environment, hence creating a conflict of cues. They concluded that some subjects used local landmarks, others global landmarks and others a combination of the two, whilst some people alternated between using local and global cues. The overall conclusion of this paper is that there appeared to be evidence that landmarks were being used by people when finding their way. Since this contrasts with earlier work (which shows only a weak effect of landmarks), it may well be that landmarks *do* play a role. It is likely that this is only one type of environmental cue used when navigating. However, Steck and Mallot also conclude their paper by endorsing the usefulness of virtual environments for this kind of research, particularly for the ability to create "conflicting environments", i.e. non-realistic environments - in this case, worlds in which environmental cues shift between subsequent journeys. They say "virtual environments are a valuable tool for navigation experiments, both for consistent and inconsistent environments."

Another component of environments hypothesised by Lynch to be crucial to wayfinding is the path (the full set being paths, edges, landmarks, nodes and districts). The use of paths in virtual worlds is investigated by Darken and Sibert in (Darken and Sibert 1996). In this study, subjects were required to perform a naïve search task in a large-scale environment representing open sea and islands. The subjects were searching for targets (ships) and the experiments took place in five different virtual (sea/island) worlds. Each task in each world was attempted under a number of conditions (with the aid of a grid, a map and both a grid and map). Darken and Sibert conclude that disorientation arises from a lack of directional, visual cues. Another unexpected observation they make is that they surmise that path-following is a natural human spatial behavioural characteristic, to such an extent that even when an *explicit* path is not evident, other environmental features such as coastlines or gridlines were used as implicit paths. This same experiment is described in more detail in (Darken and Sibert 1996), where the effects of grids (pseudo-paths) on wayfinding is that they appear to significantly improve performance. They surmise that grids are useful for providing useful orientation/directional cues.

These papers' focus upon attempts to find an empirical justification for the environmental components identified by Lynch, have led a number of researchers to attempt to use these principles in the design of virtual worlds. As stated in the beginning of this section, the dual nature of virtual wayfinding research has resulted in it concentrating upon two different applications: to inform our knowledge of wayfinding in the real world, and to design easily navigable virtual worlds. This next set of papers briefly examines research that has addressed issues of wayfinding in virtual worlds, but with the aim of improving *virtual* environment design. A large proportion of these papers have directly implemented Lynch's concepts of paths, edges, landmarks, nodes and districts as design principles for virtual world design.

For example, one such an application of Lynch-inspired design principles is the approach taken in a series of papers by Ingram and Benford (Ingram and Benford 1995; Ingram and Benford 1995; Ingram, Bowers et al. 1996; Ingram and Benford 1996; Ingram 1997). In these papers, the authors are particularly concerned with the design of abstract data-spaces and how to make them easily navigable. They examine methods to insert paths, edges, landmarks, nodes and districts into their world designs. Using their "LEADS" system, districts, landmarks and edges are computed from the spatial distribution of the data, they claim to aspire to being able to evolve paths from the movement of the users over time. Nodes are then formed by the intersection of paths. In the absence of being able to achieve path evolution at the time of their writing, paths are instead inserted into the world using computed methods.

The main problem that they encountered with this approach concerned a conflict between traditional 'paths' and the six degrees of potential movement available in the type of environments they are using. However, on the whole, they found that subjects performed wayfinding tasks in less time with repeated exposure to the "LEADS"-enhanced environments compared to plain environments. The subjects also claimed to feel less disorientated in the "LEADS"-enhanced environments. In a later paper, they also discuss Space Syntax research (Ingram and

Benford 1995), which leads them to conclude that the "subtle inter-relations between access, lines of sight, navigability and probabilities of social encounter can be exploited in the implementation of suitably designed or evolved virtual villages, towns and cities… in this way city (etc) metaphors for virtual environments may produce gradients of accessibility for information" In other words, they speculate that the use of city-like environments may serve to be useful metaphors when designing navigable abstract worlds. Ingram and Benford finally express a desire to combine both Space Syntax and Lynch-inspired approaches to aid navigation in future work on virtual worlds design.

Another important paper is that of Charitos (Charitos 1997) in which he proposes using Lynch-like components to aid navigation in the virtual world. His paper begins by describing possible examples of types of virtual landmarks, signs, boundaries (edges), thresholds (edges), places, paths, intersections (nodes) and domains (districts). Unfortunately, unlike Ingram and Benford, he makes no attempt in this paper to test the effectiveness of these objects on wayfinding task performance. The approach described in this paper remains conceptual only.

In (Darken and Sibert 1996), Darken also attempts to use some of Lynch's principles in order to investigate their effect upon wayfinding (this is in addition to his earlier work on landmarks and grids). In particular he suggests dividing the environment into smaller parts (districts) and ordering these parts using an organisational principle, such as a road network or an underlying grid. The conclusion reached by Darken was that "the presence of the wayfinding augmentations did significantly improve searching performance." although as a device, this was less useful than the provision of a virtual map. He ends this paper by noting that "Although not all wayfinding augmentations are appropriate for every problem, this research begins to show what types of information are most important, how they can be provided, and how they might be used. This is the first major step toward a methodology for designing navigable virtual worlds."

Finally, since it is felt appropriate by some researchers to apply real-world design techniques to virtual worlds to aid wayfinding, and that researchers attempting this approach appear to have met with some initial success, it is worth asking what work has been conducted into assessing the similarities between wayfinding behaviours in the real and virtual worlds. The last section of this literature review will examine what is known about the degree to which our behaviour in these two types of environment is analogous.

If we consider this final selection of papers in chronological order, it can be noted that the first paper dates from 1982. Although the experiments are not strictly conducted within a virtual environment (namely a *computer-generated* environment through which it is possible to walk in real time), this paper does compare the similarities between knowledge gained in a simulation compared to real-world knowledge. The fact that these kinds of comparisons were already being made prior to virtual environment wayfinding research is indicative of the interest in this research question. If the question underpinning this thesis is whether we can learn from the study of virtual environments how people will behave in real environments, then it is vital to understand what is already known about the similarities and differences between our behaviour in the two realms.

In (Goldin and Thorndyke 1982) Goldin and Thorndyke compare the transferability of spatial knowledge acquired in a simulated environment (in this case a film, rather than a true virtual world) to the real world. The simulated environment was a film of a route through West Los Angeles, shot from the inside of an automobile. The real tour was experienced as a bus-ride along the same route. Since it is accepted that driving through an environment will usually result in a differing pattern of environment-knowledge than walking through that same environment, then the direct relevance of this paper to this thesis could be held to be questionable. However, if the knowledge acquired in a simulated environment (albeit a driven-passenger simulation) is directly applicable to its real-world equivalent, then it may be that this transference can also be applied to different types of navigation (walking). This paper also prompts the question of whether 'walking' through an immersive virtual world is more analogous to walking in the real world, or to some other real-world situation. For example, it could actually be that walking through an immersive world is more similar to driving in the real world. This may of course be due more to motion perception and proprioception than to the visual experience.

Goldin and Thorndyke base their paper upon the theory that knowledge derived from direct navigation is superior to knowledge acquired from maps. The experiment by Goldin and Thorndyke divided their subjects into two groups: one group navigating the real environment, the other the simulated environment. (Sub-groups of each main group had their experience of the route augmented through either verbal narration or through a ten-minute map inspection). Each group was then tested for three different types of spatial knowledge; landmark knowledge, procedural knowledge (knowledge of a route) and survey knowledge (map-like knowledge). Goldin and Thorndyke predicted that there would be no difference in landmark knowledge, that the film groups should have less procedural knowledge than the real group and that the real-world group would demonstrate survey knowledge (map-like, spatial configuration knowledge) that was equal to or superior to the simulation group.

In contrast to their predictions, the simulation-group performed better on the landmark knowledge tests than the real-world group. This result could be attributed to their methodology; at every landmark, the film paused and zoomed in upon the landmark for ten seconds, making them potentially more significant than they might have been otherwise. In terms of procedural knowledge, there was no significant difference in distance and sequence estimations although the real-world group performed better for the orientation tests (approximately ten degrees more accurate in their estimations). To the surprise of Goldin and Thorndyke, the supplementary information (narration and map) did not appear to contribute to procedural knowledge. Finally, for the survey knowledge tests, there was no difference between the real group and the simulation group, excluding those members of the simulation group who also had access to a map (this subgroup out performed every other group). Although surprised by many of their results, their overall conclusions supported their hypothesis, namely, that simulations of environments can act as adequate substitutes for real-world spatial knowledge learning. The only situation where this may not be valid is where directional information is critical. For orientation tasks the simulation proved to be a less than satisfactory learning environment. However, this might not be true in an immersive world where the act of looking around is performed by a physical turning of the head or often of the whole body. Such physical body movements may help to orient a person in a virtual environment in a manner similar to the real world.

After this early paper, the remaining authors conduct their research in truly virtual environments. The first of these is (Witmer, Bailey et al. 1996), who examine how route knowledge gained in a simulation of a complex office building can be seen to aid navigation in the real building. They compare the performance of three groups; one group learns the route in the real building, the second in a virtual simulation of the building and finally one group learns the route solely from colour photographs. The subjects' spatial knowledge acquisition was measured initially by performing distance and orientation estimates. Their wayfinding ability (and hence route knowledge) was measured by recording the total time and distance travelled (using a pedometer) by each person and calculating their number of wrong turns (incorrect choices at an intersection, entering of wrong rooms and backtracking). The traversal time was almost equal for both the real and virtually trained groups, with the virtual group making slightly more wrong turns than the real group. Witmer et al. also estimate that configurational knowledge was unaffected by the method of training, and go on to conclude that "These results suggest that VEs that adequately represent real world complexity can be effective training media for learning complex routes in buildings."

Written in the same year as Witmer's paper was a paper by Tlauka and Wilson, (Tlauka and Wilson 1996). In this paper they conduct an experiment to test the spatial knowledge gained in a virtual world, compared to the knowledge gained through examining a map of the same environment. In particular they were primarily interested to see whether the knowledge gained in the virtual world was orientation-free - namely that the knowledge was flexible and independent of the orientation of the observer. Whilst instructing subjects to conduct orientation-pointing tasks, their time taken to perform the task was also measured. (The assumption being that if a subject has an orientation-specific knowledge of the world, extra time is required to mentally 'rotate' the map, before they can indicate a direction). The subjects' knowledge was tested through orientation estimates and a map-drawing task. The conclusion of this experiment was that the group that had studied the map had an orientation-specific knowledge of the world, whereas the group that had navigated through the environment had an orientation-free knowledge of the test-environment. Although this was not a direct real/virtual comparison, the important fact was that these results were similar to results found when comparing map-learnt environments to real environments. This caused Tlauka and Wilson to conclude that "the present study suggests that real-world and simulated navigation both result in similar (i.e., orientation-free) cognitive maps." They go on to say that previous work has shown that "there is a great deal of equivalence of learning in simulated and real space."

In the following year, there was a paper written by Ruddle (Ruddle, Payne et al. 1997), in which he reproduced an earlier study conducted in the real world by Thorndyke and Hayes-Roth (Thorndyke and Hayes-Roth 1982). The experiment, which had been originally constructed in a real environment, was reproduced in a desktop (non-immersive) VR. It was found that the users effectively learnt the spatial layout of the world, in a manner that was analogous to Thorndyke and Hayes-Roth's original experiment. Ruddle set three types of wayfinding test, route-finding ability (distance and time), relative distance and direction estimates. In both the real and virtual experiments, the participants were required to make direction and distance judgements. The results of these direction and distance judgements were found to be comparable with Thorndyke and Hayes-Roth's original experiment, thus enabling Ruddle to conclude that navigation in real and virtual worlds was comparable.

Finally, a series of papers written by Darken between 1997 and 1999 are all concerned with this issue of virtual-to-real knowledge transfer. (Darken and Banker 1998) (Goerger, Darken et al. 1998) and (Darken and Goerger 1999). In (Darken and Banker 1998), they concluded that exposure to a virtual simulation subsequently improved wayfinding performance in the real world. This particular experiment was conducted in a natural rather than man-made environment, and the task being performed was an orienteering[11] task. One group rehearsed the route using maps, the other using a virtual simulation. The performance of the subjects was monitored in a number of ways, and their actual paths through the environment were measured using a GPS[12] system. The result that Darken and Banker found by conducting this experiment was that a subject's level of prior experience of orienteering (beginner, intermediate or advanced) appeared to make the greatest difference to the experiment outcome. However, Darken ultimately concluded that a virtual environment was a useful training environment and that it had an added advantage which was that it was quicker (and less tiring) to train in the simulation compared to the real world.

In another study made by Goerger and Darken et al. in the same year, they performed a similar experiment in a complex building. This time they found, in contrast to all of the studies outlined above, the group that studied only a floor plan of the building performed *more* effectively than the group which trained in a virtual simulation. In the face of evidence from other papers (in particular the work by Witmer), they are unable to conclude that virtual environments are of no use for spatial knowledge transfer. However, they conjecture that their seemingly contrary results were due to the reduced time spent training in the virtual environment compared to the relative complexity of the environment. It may be that the more complex an environment becomes, the more time is needed familiarising oneself with the world.

Waller also stresses the time spent in a virtual simulation as being key to spatial knowledge-acquisition. In his paper (Waller, Hunt et al. 1998) he compares the wayfinding performance of subjects trained using a map, using the real world, a desk-top virtual simulation or an immersive virtual simulation (with both long and short exposure times). He concludes that, when only a short time period is spent in the virtual simulation, there is no advantage gained over using a map. However, with sufficient time spent in the virtual world, subjects can out-perform those trained in the real world. They conclude that, "With a few caveats, VEs can be an effective medium in which to train spatial knowledge."

Other researchers in the field broadly support the conclusion of Waller. Below are gathered a selection of quotations that effectively summarise what researchers in the field of virtual wayfinding are saying about the relationship between navigation in the real world:

- In (Darken and Sibert 1993) they conclude that "principles extracted from real world navigation… can be seen to apply in virtual environments."
- In (Witmer, Bailey et al. 1996), they state that, "These results suggest that VEs that adequately represent real world complexity can be effective training media for learning complex routes in buildings."
- In (Tlauka and Wilson 1996) they conclude that "navigation in computer-simulated space and real space lead to similar kinds of spatial knowledge."

However, a couple of notes of caution are voiced;

- "With a few caveats, VEs can be an effective medium in which to train spatial knowledge." (Waller, Hunt et al. 1998)
- "We need to better understand how spatial knowledge is acquired." (Goerger, Darken et al. 1998)

All of the above authors appear to be suggesting that we use real space and virtual space analogously, on the basis that knowledge gained in either one may be applied to the other. This result clearly has many applications, such as training people to navigate through environments that they are unable to use in the real world for training purposes. This can be because the real environment is hazardous (fire-fighting simulations or other emergency scenarios), or inaccessible (space simulations, hostage rescue situations) or does not (yet) exist in the real world.

However, the assumption that we navigate through real space in a manner that is analogous to virtual space based on evidence of knowledge transfer (between realms), is a fundamentally flawed assumption. Although the similarity of spatial knowledge gained in these two realms certainly supports the notion that real and virtual behaviour is analogous, by itself it is not sufficient evidence. In order to evaluate whether this technology is a viable technology to research wayfinding and navigational behaviour in the real world, it is necessary to determine whether we actually *use* space in the same way in both domains. To answer the question of whether we can learn how people will behave in real environments from the study of virtual environments it is vital to understand the similarities and differences between our behaviour in the two realms. It may be that we do indeed use space in subtly different ways, without this affecting our overall spatial comprehension of the environment. However, the assumption currently being made is that any cumulative effect (i.e. spatial knowledge acquisition) must always be a product of the same constituent acts (micro-scale behaviours). In fact, it could be possible that the cumulative effect (in this case, spatial knowledge) may arise from differing combinations of actions in either realm. The answer to the question 'Do we use space in a manner that is analogous and are our micro-scale behaviours and actions similar in either environment?' is vital to both wayfinding research in general and to this thesis in particular. It is also a question which has yet to be adequately addressed in existing research.

Chapter Summary

At the beginning of this chapter, wayfinding research in the real world was examined. The distinction was made between researchers focussing upon knowledge in the head (the wayfinding performance of subjects) and knowledge in the world (the design and layout of the environment). It was demonstrated that with few exceptions both the wayfinding performance of subjects and the analysis of the effect of the environments had been assessed using predominantly subjective methods. A case was put forward for the development of more objective ways of analysing both wayfinding performance and the role played by the environment. In particular it was felt that it was important to consider environment and behaviour together rather than in isolation. Methods developed by different researchers for analysing wayfinding performance and the layout of the building were presented.

Once research began into wayfinding in the virtual realm, researchers took a number of different approaches. Some felt it important to study the effect of the technology and interface, to determine how to best set up experiments in order to test wayfinding performance, and reduce any effects caused by experimental methods. Other researchers performed wayfinding experiments by simply substituting the virtual world for the real world. In particular a group of researchers used the ease of computer-generated *theoretical* environments to facilitate investigations into the effects of the environment, and in particular to test out Lynch's hypothesis that landmarks are necessary visual cues to aid wayfinding. Little conclusive evidence was found to support Lynch's ideas. However, a number of researchers went on to suggest how the inclusion of not only landmarks, but also paths, nodes, districts and edges could render virtual worlds more intelligible and hence prevent disorientation in large-scale (and especially abstract) virtual worlds. Finally, a number of researchers investigated whether spatial knowledge gained in a virtual simulation of an environment could be usefully applied to the real world. The assumption made, was that if the knowledge gained in both types of environments was comparable, then wayfinding behaviour must be analogous across the realms. An argument is put forward for why this is an inadequate method for comparing real and virtual navigational behaviour. The importance of seeking answers to this, in the context of both wayfinding research (in general) and this thesis (in particular), is stressed. In order for the work of this thesis to be relevant (to either virtual navigation or real world pedestrian movement research), it is necessary to determine if the two are comparable. In the next chapter, one method for assessing this relationship will be presented, as it is felt vital to establish this fact before any further experiments can be conducted.

Key Points

- This thesis' definition of wayfinding is that it is the act of travelling to a destination by a continuous, recursive process of making route-choices whilst evaluating previous spatial decisions against constant cognition of the environment.
- Methods of measuring wayfinding ability or behaviour are inadequately developed and suffer from being subjective.
- Methods of analysing aspects of the environment and gauging the environment's effect on wayfinding performance are inadequate and also suffer from being predominately subjective measures.
- There has been little research undertaken into directly relating wayfinding performance back to the design of the environment.
- In comparing wayfinding in the real and virtual world, it has been assumed that since spatial knowledge gained in a virtual simulation may be successfully applied to the real world, therefore wayfinding behaviour in both situations must be comparable. No work has been done to determine whether we navigate in a similar manner.

- Route asymmetry (taking one route from A to B and a different route from B to A) is an interesting phenomenon that may serve as a clue to investigating wayfinding research issues.

Notes

[1] Earlier papers tend to use the word in its hyphenated form, whereas later papers tend to use the concatenated form.

[2] From The Oxford Dictionary of English Etymology and An Etymological Dictionary of the English Language, 1924.

[3] Source from The Oxford English Dictionary, Second Edition.

[4] Source A Dictionary of Americanisms, Matthews.

[5] Tetris is a simple computer puzzle game. As small shapes fall down the screen, they must be rotated to fit together to complete lines. When an entire line is filled with blocks, it is removed from the screen. If the player cannot complete lines, the blocks will eventually rise past the top of the screen and the game ends. It was invented by Alexey Pajitov in 1985 whilst at the Computer Centre of the Academy of Sciences in Moscow.

[6] Source, Raubal, M. and M. J. Egenhofer (1998). "Comparing the Complexity of Wayfinding Tasks in Built Environments." Environment and Planning B 25(6): 895-914.

[7] Source, Raubal, M. and M. Worboys (1999). "A Formal Model of the Process of Wayfinding in Built Environments." Lecture Notes in Computer Science(1661): 381-400.

[8] Source, Raubal, M., M. J. Egenhofer, et al. (1997). "Structuring Space with Image Schemata: Wayfinding in Airports as a Case Study - Spatial Information Theory - A Theoretical Basis for GIS, International Conference COSIT '97." Lecture Notes in Computer Science 1329: 85-102.

[9] Although there remains a slight problem caused by people walking at different speeds, one solution being Witmer's use of a pedometer in (Witmer, Bailey et al. 1996).

[10] "The observation that the logic density of silicon integrated circuits has closely followed the curve (bits per square inch) = 2^(t - 1962) where t is time in years; that is, the amount of information storable on a given amount of silicon has roughly doubled every year since the technology was invented. This relation, first uttered in 1964 by semiconductor engineer Gordon Moore (who co-founded Intel four years later) held until the late 1970s, at which point the doubling period slowed to 18 months. The doubling period remained at that value through time of writing (late 1999)." Source, The Jargon Dictionary, http://www.netmeg.net/jargon/terms/m/Moore_s_Law.html.

[11] A "Competitive sport in which runners cross open country with a map, compass, etc." Source Pocket Oxford Dictionary (electronic version), Oxford University Press, 1994.

[12] Global Positioning Satellite. A system whereby a user's location is determined by triangulating their distances from a number of satellites in stationary orbit. The accuracy of different systems varies.

Chapter Three:
A Comparison of Real and Virtual 'Pedestrian' Movement

Abstract

This chapter aims to establish whether we move through virtual worlds in a manner that is analogous to our behaviour in the real world. The virtual, test environment being used for this study is a simulation of the Tate Gallery, Millbank, London. The first section of this chapter presents a detailed description of how the experiment was performed, describing in turn the environment, subjects, apparatus, procedure and methods/format of data retrieval. The chapter continues by demonstrating how the raw, navigation-data output from the experiments may be transformed into a graphical representation of the paths taken by subjects through the gallery. The virtual navigational data are compared to movement observations of people made during the first ten minutes of their visit to the real Tate Gallery. A strong statistical correlation is demonstrated between the two data sets. The encouraging results and conclusions of this chapter lead to the performance of a number of wayfinding experiments; these experiments take place in a series of virtual worlds specifically designed to test different spatial variables. These subsequent experiments and their results are described in Chapter 4.

Introduction

The previous chapter concluded by noting that patterns of navigation in virtual worlds are deemed to be similar to real-world pedestrian movement since spatial knowledge can be demonstrated to be transferable between the realms. Additionally it was observed that no previous experiments have been undertaken to investigate whether the actual movement patterns are similar. This chapter will use observations of pedestrian movement in a real environment to compare to movement patterns in a virtual simulation of the same environment. The Tate Gallery (Millbank) was selected as the environment to be simulated and there were two reasons for its selection. Firstly, the building had already been the focus of a previous research study and hence a lot of information was already known about how real people moved through this particular environment. Secondly, the building has only one primary entrance and therefore visitors entering the building can easily be tracked from this single location. In the simulation, subjects also enter the virtual environment at one location (it is far more difficult to randomly vary their starting positions). By using a real and virtual environment where all people enter at the same location, the two data sets are more easily comparable. At the time of conducting this pilot study, only the Tate Gallery fulfilled both of these criteria.

It would be possible to simply correlate the virtual navigation data with configurational measures of the spatial layout of the building. Since it is already known that the patterns of real movement correlate highly with such measures[1] it would be possible to conclude that this should prove that real and virtual movement are analogous. Since both patterns of movement correlate with spatial analyses of the environment, they must therefore also correlate with each other. However, it is a more powerful proof to directly compare real and virtual movement. It is for this reason that spatial analyses of the environment are not used directly in this chapter instead they will be introduced in the following chapter.

Background to the Real Data

In 1995 the Tate Gallery was considering changing the location of its main entrance and required an indication of the effect that such a change might have on existing patterns of pedestrian movement. A group of researchers at the Bartlett School of Architecture, University College London, were approached to try to answer their question. Their first task was to comprehensively observe the existing patterns of visitor movement. These observations took place in September 1995 and subsequently provided the real world observational data which have been used as the background to the virtual Tate Gallery experiment. The real world observational data was shown to correlate extremely well with configurational measures of the layout.

In the original study the following kinds of observations were made:

Gate Counts

This data represents the cumulative number of people passing over a specified 'threshold' within a given timeframe.

Spot Counts

This is a graphical representation indicating the approximate location of all people present in any room or space at a given moment in time.

Occupancy Numbers

These are simply the total numbers of people present in a single space/room during specific time intervals throughout the day.

Movement Traces

A researcher 'picks up' a subject at the main entrance of the real Tate Gallery and follows them for a period of ten minutes. Whilst following them, the observer marks the subject's approximate route onto a plan of the building. The movement path of the subject is represented as a single line on the plan. After a specified interval (ten minutes in the Tate Gallery) the researcher returns to the main entrance, collects another subject and repeats the procedure. The researchers are experienced at conducting such observations with discretion and the subjects are unaware that their movements are being recorded. This method of observation constitutes the data set that was selected to be emulated in the virtual experiment.

The Experiments

Subjects

The subjects in this experiment were twenty-five unpaid volunteers, with a male to female ratio of 3:1. Their experience of virtual environments ranged from no experience at all to some experience and familiarity of such technology. The subjects were primarily students and researchers at University College London. No questionnaires were given to these subjects and consequently additional data, such as ages, were unavailable for this group.

Apparatus

The computer used for the experiment was a Silicon Graphics Indigo2 IMPACT workstation running Division's dVS/dVISE developer software, version 3.1.0. The peripherals used in conjunction with this computer were Division's dVISOR head-mounted display and a Division 3d mouse. The dVISOR helmet provides the subject with an immersive, stereo, full colour LCD visual display and a wide field of view. The horizontal field of view of this headset is 105° with a vertical field of view of 41° and a 40° horizontal overlap[2]. This particular headset has a far greater field of view than the majority of commercially available headsets, which have an average field of view of between 40°-60°. The inter-ocular[3] distance of the system was set to 2.55 inches or 64.77 millimetres (the default value).

The virtual Tate Gallery was initially modelled using the 2d and 3d CAD application MicroStation 95 by Bentley Systems. A 3d model of the gallery was created in MicroStation and then exported as a 3d DXF[4] file. This data was then translated from DXF into Division and the model was further developed (lighting, collision detection and a soundtrack were applied) using Division's own software. A user event programmed into the world using Division's dVISE scripting language calculated the position of the subject in the virtual world and the orientation of their head (broadly analogous to their direction of gaze) ten times every second and saved it as an ASCII[5] text log file. A small programme written in the C programming language translated the ASCII text output file into a 2d CAD format (in this case MiniCad 7.0.3[6] by Diehl Graphsoft) for data visualisation purposes. Since an ASCII log file contained information regarding the location and direction of gaze of a subject, sampled ten times every second, the following information could be directly calculated from this data.

- Continuous path of movement of a person.
- Location of a person at any moment of time during their journey.
- Location of a person's 'Pause Points' or 'Dwell Points'.
- Total number of a subject's 'Pause Points' or 'Dwell Points'.
- Proportion of the journey spent stationary by any person.
- Total distance travelled & total journey time.
- Average velocity/acceleration over the journey.
- Continuous locus of the orientation of the head mounted display.
- Approximate direction of a subject's gaze whilst stationary.

The subject's 'body' within the virtual environment is scaled appropriately (the entire world is constructed at a 1:1 scale, i.e. full size) with the eye height of their virtual body set at 1.6m above the ground plane. This eye height was maintained for all subjects unlike some researchers such as Ruddle[7] who set the eye height of the virtual body to the eye height of each individual subject prior to starting the experiment. It is not possible to fly through this world, i.e. the subject can only move in directions parallel to and at a fixed height above the ground plane. Since the primary aim of this experiment was to compare patterns of virtual navigation to pedestrian movement in the real world, it was decided to utilise appropriate constraints in order to make the virtual world experience as analogous to the real world as possible. Since we do not fly in the real world subjects were unable to fly in the virtual world (although the software could have allowed them to do so). Another reason for preventing flying was suggested by Darken in (Darken and Sibert 1993). In this paper, Darken and Sibert experimented with permitting subjects to fly above the world as an aid to spatial navigation. It was evident that both hovering and flying above the world effectively changed the scale at which the subjects viewed the world. Because of this scale-change, Darken and Sibert speculated that the subject's task became more analogous to map reading that it did to navigation (as experienced in the real world). Another constraint imposed upon the subjects in order to make their experience of the virtual world seem similar to their experiences of the real world was to ensure that none of the subjects were able to walk through walls.

Virtual motion in these experiments was further constrained to forwards, backwards and horizontal rotations (turning) only[8], controlled by the subject using the 3d mouse provided. The speed at which the subject could move around the world was also constrained to an average walking speed (taken to be four miles per hour or 1.79 m/s). With such a speed restriction in place, a circuitous route through a virtual environment required a greater amount of time to reach a destination compared to a shorter route (as per the real world). It was hoped that this time penalty would encourage subjects to take routes that are more efficient in later wayfinding experiments. The primary difference between the virtual and real world experiences is the absence of an equivalent increase in physical exertion by the subject when taking a circuitous route in the real world.

In the Tate Gallery experiment, a stereo, audio soundtrack was played through two speakers located in the headset. The soundtrack played ambient music on a repeat loop. Although it was felt that the inclusion of a soundtrack had not detracted from the experiment in any way, it was also felt that it had not really contributed to it either. In particular, the aim had been that the use of sound would cause the subjects to feel more 'present' in the virtual world. Since experiments conducted into virtual presence and task performance, as discussed by Witmer and Singer (Witmer and Singer 1998), seemed to suggest that presence has a positive effect upon task performance, it was surmised that this phenomenon could be used to good effect in this and subsequent experiments. It had been hoped that if the subjects felt more *present* in the environment, they would perform any spatial navigation tasks set them in a manner *more* akin to the real world, than if they felt less present in the environment. After talking to the participating subjects, it was clear that there was no evidence that the soundtrack had been of any use and therefore the inclusion of a soundtrack was not used for subsequent experiments. It was concluded that the use of sound might increase the sense of presence if, and only if, it is *appropriate* sound i.e. there is a strong congruity between the visual and audio-scene.

Format of Data

Figure 3.1 below is an example extract of a typical data log file. This shows the actual data sampled ten times per second and the format in which it was saved. The first three numbers of the body position are the x y and z co-ordinates of the position of the subject's head. Note that the y co-ordinate (or height above the ground plane) remains a constant 1.6 metre (eye height). The second set of numbers, termed 'orientation', represents the direction of gaze of the subject. Each number indicates an angle of rotation about an axis; in this case, these are the x y and z-axes respectively. The lines of text that are coloured grey indicate a brief moment when the subject is stationary (the first three numbers do not change) but is looking around (the last set of numbers are changing).

```
Body position (-25.5982, 1.60000, 42.9879) orientation (-14.2102, 139.612, 0.822218)
Body position (-26.023, 1.60000, 43.4645) orientation (-14.2258, 136.79, 0.841104)
Body position (-26.2623, 1.60000, 43.6935) orientation (-13.9041, 127.983, 1.67329)
Body position (-26.2623, 1.60000, 43.6935) orientation (-13.7864, 123.418, 1.43876)
Body position (-26.2623, 1.60000, 43.6935) orientation (-13.3516, 118.509, 1.94654)
Body position (-26.2623, 1.60000, 43.6935) orientation (-13.2794, 113.833, 2.23407)
Body position (-26.2623, 1.60000, 43.6935) orientation (-13.7588, 110.555, 2.56719)
Body position (-26.2623, 1.60000, 43.6935) orientation (-13.8716, 111.295, 2.66312)
Body position (-26.2623, 1.60000, 43.6935) orientation (-14.2966, 113.453, 2.64884)
Body position (-26.2623, 1.60000, 43.6935) orientation (-14.4233, 118.556, 2.546)
Body position (-26.7796, 1.60000, 44.0907) orientation (-15.0828, 131.033, 0.736862)
Body position (-27.2976, 1.60000, 44.6415) orientation (-15.995, 139.864, -0.510866)
Body position (-27.7012, 1.60000, 45.1304) orientation (-16.0784, 140.105, -0.408339)
```

Subject is Stationary

Figure 3.1 Extract from a Typical Log File

Procedure

There is an excellent definition of the various types of spatial search activity given by Darken (Darken and Sibert 1993), where they suggest that,

> "*exploration*, [is] where the primary goal is gaining familiarity with the environment; *naïve search*, where the subject is searching for an object when its appearance but not its location, is known; and *informed search*, when the subject has some knowledge about the location of the object."

Using this definition, it can be stated that the Tate Gallery experiment was an example of *exploration*. In this study, the subjects all began the experiment at the main entrance to the building, facing towards its main central axis. They were not informed which real world building the virtual environment was simulating and there were no clues inside the building to its function. (When asked, after the experiment had finished, to guess the identity of the real building, only one subject out of 24 guessed correctly). The subjects were instructed that they had up to ten minutes to explore the building (or to 'wander at will') at which point they were to attempt to return to their original starting location. If at any point throughout the experiment they wished to leave the virtual building they could do so, although they were encouraged to attempt to return to their starting location when they had tired of their exploration. The average amount of time that people spent in the virtual Tate Gallery was 9.35 minutes compared to ten minutes in the real Tate Gallery. The decision to allow subjects to leave the virtual gallery before the ten-minute limit expired was made with the sole intention of preventing motion sickness amongst the subjects.

Description of the Virtual Tate Gallery

The original data from which the virtual world was constructed was provided by the Tate Gallery in the form of 2d DXF plans (see figure 3.2 below).

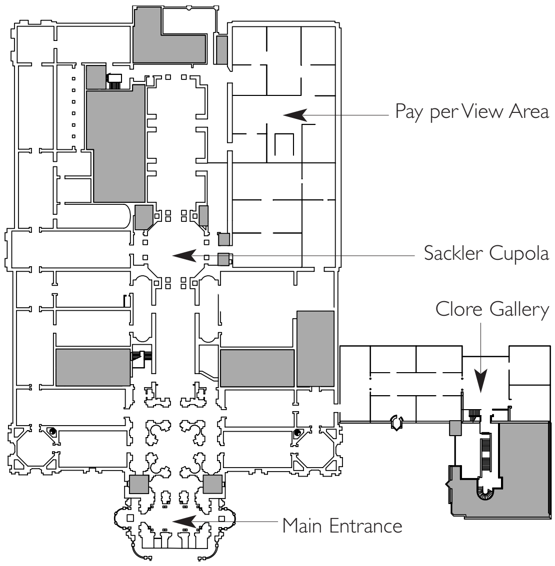


Figure 3.2 Plan of the Tate Gallery

Visually, there are no textures in this environment, nor in this particular world are there any simulated paintings, sculptures or any other visual stimuli, which could be used as 'landmarks' to aid navigation. The floor-to-ceiling heights were modelled to be a constant height without any detail (such as domes, vaulted roofs, ornamentation etc.). In essence, this model only consisted of basic forms and spaces. Furthermore, the virtual world simulat-

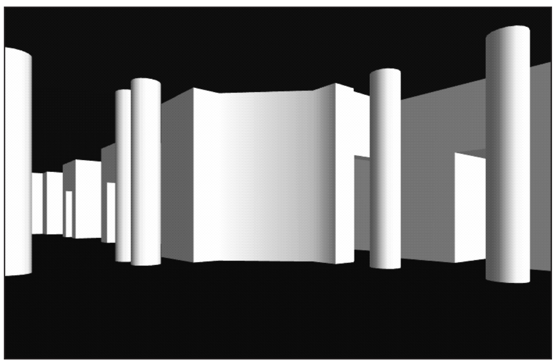


Figure 3.3 Screenshot of the Virtual Tate

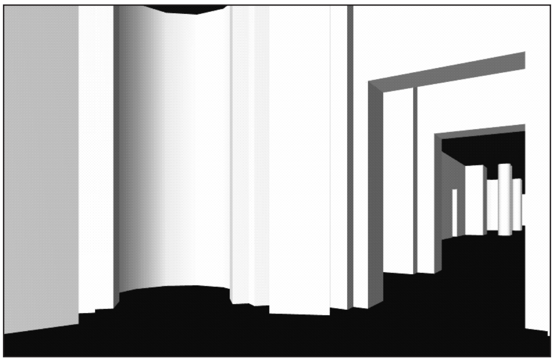


Figure 3.4 Screenshot of the Virtual Tate

ed only the ground floor of the Tate Gallery. The real Tate Gallery, in Pimlico, has basement and first floor levels, but these were excluded from the virtual model. Stairwells were treated as rooms into which a subject could enter and yet led nowhere. Part of the real Tate Gallery contains a 'pay-per-view' area, which is inaccessible to the general public; admittance is allowed only to those who pay to see a particular exhibition. In the virtual Tate, no such hierarchy of space was imposed. Space was either accessible or inaccessible. Certain galleries, which were 'closed' at the time of the original real Tate observations (for refurbishment or picture-hanging) were also treated as 'closed' in the virtual Tate. The overall size of the virtual Tate Gallery (at its greatest extents) is 89.0 metres by 90.6 metres. See Figures 3.3 and 3.4 for screenshots of the virtual Tate model.

A summary of the various similarities and differences between the real and virtual galleries are presented in table 3.1 opposite along with comparative images of the real and virtual Tate galleries. The items that are indicated by an asterisk refer to the navigational properties of the two galleries.

The wealth of data available from a subject immersed within a virtual environment is significantly greater than that of the same subject within a real environment. The methods of pedestrian obser-

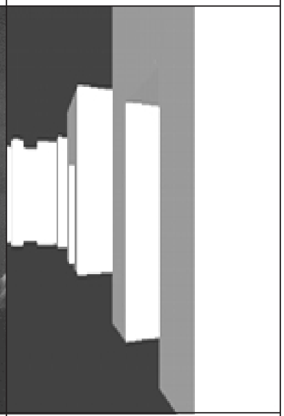
Real Tate Gallery	Virtual Tate Gallery
	
Pictures	No Pictures
Multiple levels	Ground floor model only
Doorways (with doors, but usually wedged open)	Just the doorways (the openings only)
Entry at main entrance (and secondary entrance through the Clore Gallery)	Entry at main entrance
Contains furniture – seats and benches	No furniture
Some areas are closed to the general public (as in September 1995)	The same areas are inaccessible in the virtual model
Other people	No other people (although it could have been used in multi-user mode)
Areas in which one needs to pay for access (temporary exhibitions)	No payment or varying degrees of access in the virtual Tate
Surfaces – wall colours and surface textures differ between rooms	All walls have the same wall colour and texture
Differing ceiling heights and roof details	Constant ceiling heights throughout the gallery
Varied lighting	Even, constant lighting
Ambient background noise of other people using the gallery	Ambient background music
Solidity - cannot pass through the walls*	Solidity – cannot pass through the walls*
Cannot fly (effect of *gravity* in the real world)*	Cannot fly (constrained to the ground plane)*
Constrained to walking speed (albeit a *social* restraint only)*	Constrained to walking speed of 1.79 m/s*

Table 3.1 Summary of Differences between the Real and Virtual Tate Galleries

vation within the real world are limited in comparison and have changed little over the last couple of decades. Essentially real world observations are interpretations and approximations made by the observer of the location of the subject at any given moment within the set study area (urban area or building). Although the two methods of gathering the data are quite different, the cumulative results of the observations may be represented in an identical manner. The path of each person may be indicated by a single, continuous line marked onto the plan of the building. In this manner, figures 3.5 and 3.6 represent the paths taken by subjects in the real and virtual versions of the Tate Gallery.

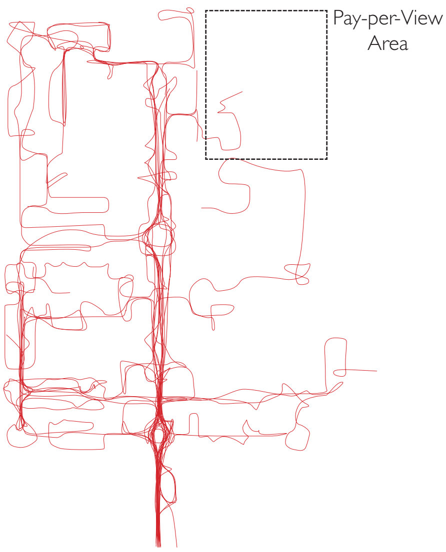


Figure 3.5 The Movement Traces for all Subjects in the Real Tate Gallery

At first glance, the patterns of movement seem more dissimilar than similar. In the real Tate, people can be seen to be walking around the edges of rooms (possibly looking at paintings or because of the central positioning of furniture or both). In contrast, people in the virtual Tate can be seen to be moving through the centres of spaces. However, at a more generalised level, the central axis in both galleries

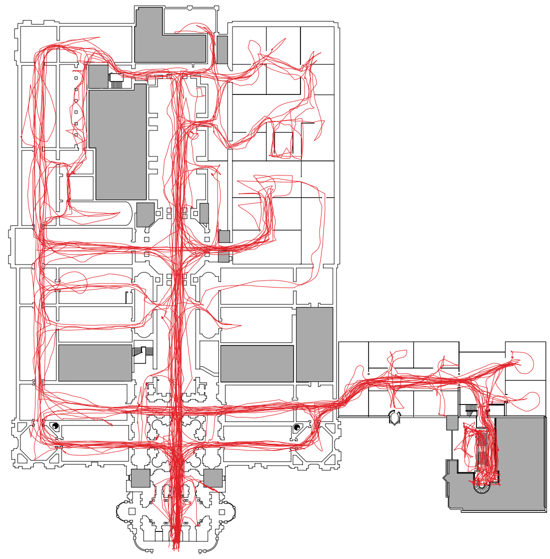


Figure 3.6 The Movement Traces for all Subjects in the Virtual Tate Gallery

dominates the pattern of space use. This is mirrored, to a lesser degree, by the axis running down the left-most side of the building plan. The right-most galleries in both environments are underused. This information can be gained by visually comparing the patterns of real and virtual through-movement.

In order to compare the two data sets it is first necessary to represent each data set in such a manner that the two may be directly correlated. The method chosen in this thesis is to represent each data set as a series of cumulative threshold counts. Every doorway located on the ground floor of the Tate Gallery is assigned a unique identifying number, and is given an attribute, 'number of people'. This attribute is initially set to zero for all thresholds. This doorway or threshold can also be indicated by a rectangle drawn onto the plan of the building. Firstly, the real observation data needs to be transformed into a set of cumulative threshold counts. Each person's movement trail is carefully examined. Every time a subject passes through a doorway the value of that particular doorway or threshold is incremented by the integer value 'one'. This process is repeated for all the subjects in the data set. At the end of this process, the attribute 'number of people' for each threshold will have a value ranging from zero to n (n being the maximum number of people to pass through any single doorway). This information can also be illustrated visually by using the rectangles that represent the doorways on the plan. These rectangles can be assigned a colour according to their 'cumulative person' value. For example, a red rectangle could represent the *highest* number of people to have passed through a doorway, a blue rectangle could represent the lowest and values in between represented by a 'rainbow' spectrum from red to blue.

This process must then be repeated for the virtual data set. Of course, to speed up such a laborious procedure all the calculations are automated by using a specifically written computer application[9]. After the second data set has been processed in this way, every doorway will have two different numbers associated with it. These are the number of real people to have passed through that particular doorway and the corresponding number of virtual people to have also passed though it. The two visual representations of the same information can also be a useful indication of similarities and differences between the two data sets. By representing the quantitative information visually, it can be possible to perceive patterns and trends that it would be difficult to identify if the data were only presented numerically.

Once the numerical values of virtual and real cumulative pedestrian counts have been calculated, one set of data can be plotted against the other. Figure 3.9 overleaf is a scattergram showing real pedestrian movement data plotted against virtual navigational data. The correlation between these two data sets is

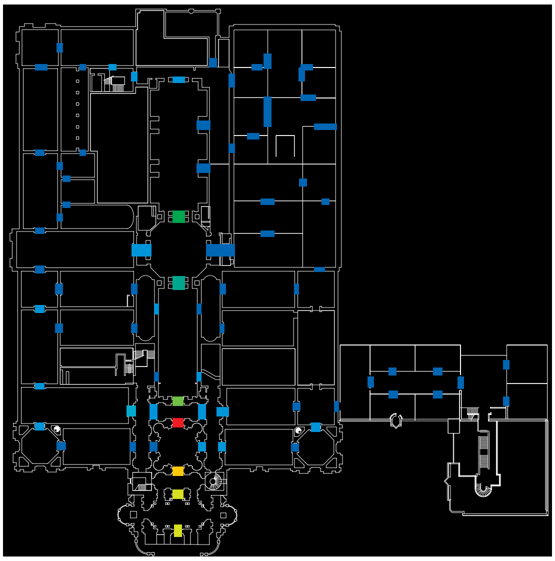


Figure 3.7 Real Cumulative Threshold Counts

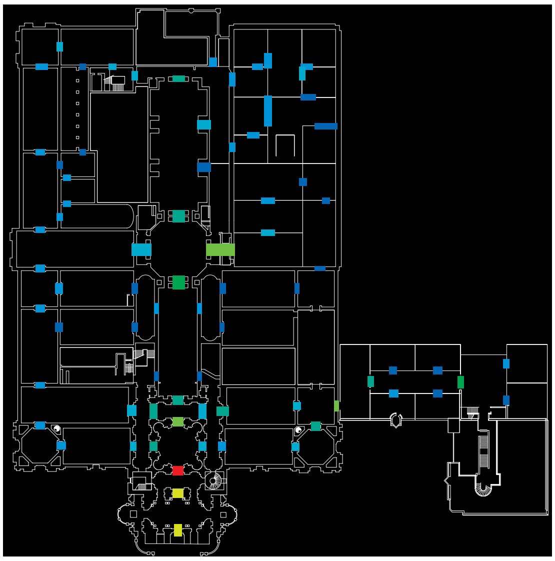


Figure 3.8 Virtual Cumulative Threshold Counts

0.458 r-squared, which is a positive correlation and suggests that there is a relationship between the two sets of values. The dots that are circled indicate thresholds located in the Clore Gallery.

If the two visualisations of cumulative threshold counts, figures 3.7 and 3.8 above, are examined, the Clore Gallery, which is the more recent extension (by the architect James Stirling) is clearly identifiable on the bottom right of the plan. It is clear that the thresholds in the virtual Clore have much

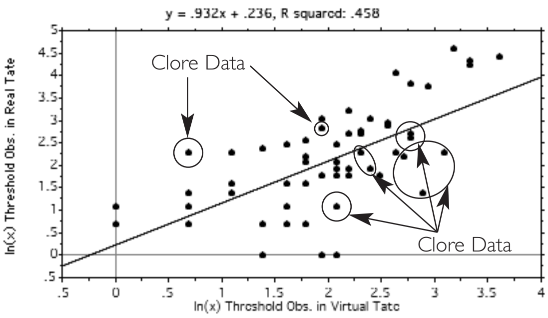


Figure 3.9 Correlation of Real to Virtual Threshold Counts

greater numbers of people passing through them than their real world equivalents. This observation is confirmed if the scattergram of the two sets of data is regenerated, this time excluding the Clore Gallery data. Now the correlation between real and virtual movement is more significant, having a value for r-squared of 0.521 instead of 0.458.

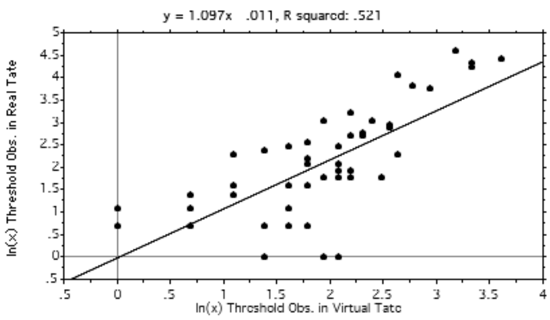


Figure 3.10 Correlation of Real to Virtual Threshold Counts (Excluding the Clore Data)

In the virtual Tate Gallery, there are two distinct routes from the main gallery into the Clore. If the virtual navigation data, figure 3.6, is examined it can clearly be seen that the numbers of people entering the Clore are equally divided between these two routes. Let these routes be termed the 'lower route' and the 'upper route'. In the real Tate Gallery, the lower route is not really a route at all as it is the gallery bookshop. Although this space can be used as a route from the main gallery to the Clore, in actual fact, this path is visually obscured by eye-level sales displays and therefore the through-route becomes quite convoluted and complex. In the virtual Tate, no such visual impediments exist, and the route through the bookshop is as viable a route to the Clore as the upper route (which is in fact the intended route to the Clore). In the virtual gallery, there are twice as many people who find their way to the Clore compared to the real Tate. This finding makes sense since there are two virtual routes in contrast to the one real route. By discounting the threshold counts for the Clore gallery the correlation between the two data sets changes to 0.521 r-squared. This is a highly significant correlation.

The fact that there is any correlation was unforeseen; the fact that there is such a good correlation (both the r-squared values of 0.458 and 0.521 represent statistically significant correlations) is a notable outcome. To summarise, in the real Tate Gallery subjects were moving around, surrounded by other people, looking at paintings and sculptures. In the virtual Tate, the subjects were moving through the building, alone, without anything to look at (neither pictures nor sculptures). It seems almost counter-intuitive that the correlation of the movement patterns should be so good. The result of such a good correlation implies that the building plays a far greater role in determining the paths that people are taking through the building than *either* the layout *or* art curation of the galleries. This is not to say that art curators have no contribution to make to the overall success or failure of a gallery. Rather, it stresses the fact that it is of utmost importance that the building should function well as a gallery. If a gallery functions well the art curation can be used to *reinforce* a well designed building, rather than a curator needing to use all his/her skills to overcome inherent deficiencies in a gallery's layout.

Conclusions

It appears that there *is* a relationship between pedestrian movement in the real Tate Gallery and patterns of navigation in a virtual simulation of the gallery. This relationship exists despite intrinsic differences such as the fact that there were no pictures in the virtual simulation (refer to table 3.1 for comparative details). However, it cannot be stressed strongly enough that this chapter presents the results of only one experiment. There is a need for additional research to take place that should use a larger number and broader range of environments in order to build upon this result. However, an early, positive correlation can be used to justify such future experiments. It is hoped that the Tate Gallery may become the first in a series of simulations (that range from buildings to different types of urban areas) to be used to further explore this relationship. Understanding the relationship between real and virtual movement is an important task as many researchers (particularly in the area of wayfinding research) have assumed that results from their virtual experiments *must* imply an equivalent real world interpretation (See Chapter 2). Having tentatively demonstrated in this chapter that there is some kind of relationship between these two data sets, it becomes necessary to highlight the fact that this relationship might not represent an exact mapping between pedestrian movement and virtual navigation. However, if further research can be undertaken into understanding this relationship, then in the future it may be possible to extrapolate from one to the other.

One question posed in the preceding chapters was whether it was possible to learn about people's behaviour in the real world based upon equivalent behaviours in the virtual world. Although the correlation between real and virtual movement as demonstrated in this chapter does begin to suggest a positive answer to this question, a tentative 'yes' is tempered by a need to reproduce this result for different types of environments. However, this experiment can serve to pave the way for a series of wayfinding experiments in different worlds enabling the examination of alternative micro-scale behaviours, namely the following experiments that form the main body of this thesis. In the following chapter, a number of different environments are designed with the intention of testing the effect of specific spatial variables. A number of different types of behaviour can be examined, thus investigating whether it is possible to identify small-scale behaviours which when aggregated produce pedestrian movement patterns. The worlds, the experiments and the resultant data will be presented in the following chapter.

Key Points

- It is possible to use virtual environments to gather data regarding people's behaviour in virtual worlds.
- People's behaviour can be sampled quite rapidly, in the case of these experiments at a rate of ten times per second. This rate exceeds the rate at which we can, with ease, observe similar behaviour in the real world.
- Subjects found it easy to navigate through these environments immersively. The learning curve, to learn how to move through these worlds, was very shallow, making the technology ideal for such experiments.
- It appears that people are moving through the virtual worlds in a manner that is analogous to the way in which we navigate in real environments.
- It is vital to create the same kinds of circumstances when making the real and virtual obser-

vations. The more similar the simulation is to the real environment the better the resultant correlation is likely to be.

Notes

1 the outcome of the original study, see Hillier, B., M. D. Major, et al. (1996). Tate Gallery, Millbank: a Study of the Existing Layout and New Masterplan Proposal. London, Bartlett School of Graduate Studies, University College London.

2 Compare this to real-world vision, which has a horizontal field of view of approximately 180° (for binocular vision) and a vertical field of view of approximately 120°.

3 The inter-ocular distance is the shortest distance between the two centres of a subject's eyes.

4 DXF is a graphics file format originally created by AutoDesk, the makers of AutoCAD. 'DXF' stands for 'Drawing eXchange Format', and is widely supported by nearly all CAD programs.

5 ASCII is an abbreviation for the American Standard Code for Information Interchange. It is a plain text format.

6 At the time of the publication of this thesis, later versions of MiniCad have been renamed VectorWorks.

7 Source from a verbal conversation with Ruddle in 1998.

8 I.e. subjects were unable to pitch forwards or backwards or lean sideways.

9 The application was called 'ThresholdCheck' and was written in SuperCard using the scripting language SuperTalk (similar to HyperTalk). The application was written specifically for this thesis.

Chapter Four:
Virtual Wayfinding Experiments and Movement Paths

Abstract

This chapter presents each of six worlds, which constitute the experiment stimuli, each environment being described in terms of its visual, formal and spatial attributes. The worlds have all been selected or designed to test different spatial variables and these criteria are fully explained. The results of basic spatial analyses of each of the seven worlds are presented with accompanying interpretations and explanations. Included in this chapter are the equivalent spatial analyses of the Tate Gallery, which is presented here for comparative purposes as the Tate movement data will also be used later in the thesis. The initial results of the experiments expressed as movement traces are discussed in the light of what is already known about pedestrian movement from Space Syntax research. This chapter concludes by noting which routes are most popular in each environment.

Introduction

The results of the previous pilot-study were encouraging since they suggested that real and virtual movement were comparable. It appears, therefore, that such methods can be used to attempt to determine what can be learnt from virtual environments about how people will behave in the real world. Using the results of virtual-world experiments to provide detailed observational data of small-scale actions, it could be possible to investigate how aggregate patterns of movement might arise from such actions. In order to study the problem it is first necessary to gather data from more environments than the single building used for the pilot-study. Therefore, it is necessary to perform more experiments and to set these experiments in a wider range of environments: both building-scale and urban-scale, intelligible and unintelligible[1] and 'real simulations' and fictional, theoretic environments. The environments used for these studies were selected or designed with the research question in mind. An explanation of the experiment procedure and the environments in which the experiments were conducted is given next.

The Experiments

Introduction to the experiments

The experiment apparatus is identical to the set-up used in the Tate Gallery Experiment, as described at the beginning of the previous chapter, Chapter 3. Seven virtual worlds and seven[2] discrete tests constitute the experiments that form the empirical component of this thesis. The description of these seven experiments and virtual environments forms the primary focus of this chapter. The first world served as a pilot-study and consequently this experiment took place at an earlier date and used a different group of volunteers to the other tests. This pilot-study will now be termed 'World A' (the Tate Gallery). The experiment conducted using 'World B' was also performed at an earlier stage, whereas the experiments that used Worlds C-G all took place at the same time and used the same group of subjects. All the worlds, the names (if any), descriptions and total numbers of subjects participating in each experiment are presented in the table below, table 4.1.

World Name	World Code No.	Subjects	Characteristics of World
Pilot-Study 1 - Tate Gallery	A	24	Simulation of a real world building.
Pilot-Study 2	B	36	Uniform length axial lines, terminating at 90° T-junctions. Monument in centre.
Intelligible Urban World	C	31	One of a pair of comparative-worlds. Each world contains the same buildings with minor changes in position (& significant spatial differences).
Unintelligible Urban World	D	31	One of a pair of comparative-worlds. Each world contains the same buildings with minor changes in position (& significant spatial differences).
Triangular Grid World	E	31	Uniform length axial lines, crossing at a variety of angles ranging from 60° to 180°. Relatively unintelligible. Designed to test angles of incidence of route choice.
Square Grid World	F	31	One of the examples from *Space is the Machine*. Urban blocks are double squares.
Barnsbury	G	31	Real world simulation of part of Islington, London.

Table 4.1 Table of Distinctive Characteristics of Worlds

The plans of the worlds are shown overleaf in figure 4.1. The locations where the subjects entered the worlds are indicated by arrows marked onto the plans. The plans are labelled A through to G corresponding to the code for each environment as described in table 4.1 overleaf.

'World B' was designed as a second pilot-study to determine whether 'theoretical' worlds (worlds which are *not* simulations of a real environment) can be used to examine micro-scale behaviour. This world was designed to contain roads of equal length so that we can explore whether people's route choice decisions are affected by road length. The majority of the road junctions in this world are T-junctions where the subject is presented with a clear left or right choice. Using these two rules (a single road length and single junction type), a world was generated which could be used to test the route-choice decisions made at junctions. This was one type of small-scale action that could contribute to producing aggregate patterns of movement as observed at the larger scale.

The next pair of worlds, 'Worlds C and D' are spatially interesting. They were designed by Hillier and described in his book *Space is the Machine* (Hillier 1996) as examples of intelligible and unintelligible environments. What is particularly interesting about this pair of worlds is that Hillier manages to transform an extremely intelligible world into an unintelligible environment by doing nothing more than *slightly* altering the location of some of the buildings. This pair of worlds was chosen, therefore, to determine whether such small changes could have a significant effect on pedestrian movement. Does the intelligibility of an environment affect our small-scale actions?

The next world became known as 'triangular grid world'. This environment shares some similarities with 'World B' in that all of its roads are also of equal length. However, unlike World B, which was designed with only one junction type (the T-junction), in World E, an attempt was made to use as *many* junction-types as possible. Above all other worlds, this world was designed to test the *kinds* of choices made at decision points. The decisions made at road-junctions were hypothesised as being significant types of small-scale action, such that an understanding of these decisions alone might be sufficient to comprehend the connection between small-scale actions and movement as an emergent phenomenon.

'World F' was an example from Hillier's book 'Space is the Machine' (Hillier 1996). It was chosen because it was decided that the sample should include a world based on a rectilinear grid, but one that contained roads of *varying* lengths. In this world, the majority of junctions are either T-junctions or crossroads and it is the lengths of roads that vary most. It was intended to use this environment to test the effect, if any, of road length on movement. In Space Syntax terms, this environment is highly intelligible and hence was felt to be ideal for the purposes of this thesis.

Finally, 'World G' – Barnsbury in Islington, London - was selected as it was felt that it could be useful to include another real world simulation in the set of environments. Since 'World A' was a building it was decided that World G should be an urban environment or district. Barnsbury was chosen for 'historical' reasons as it has been widely published in many Space Syntax books and papers (for example (Hillier and Hanson 1984)) and therefore is a part of London with which academics in the field are familiar.

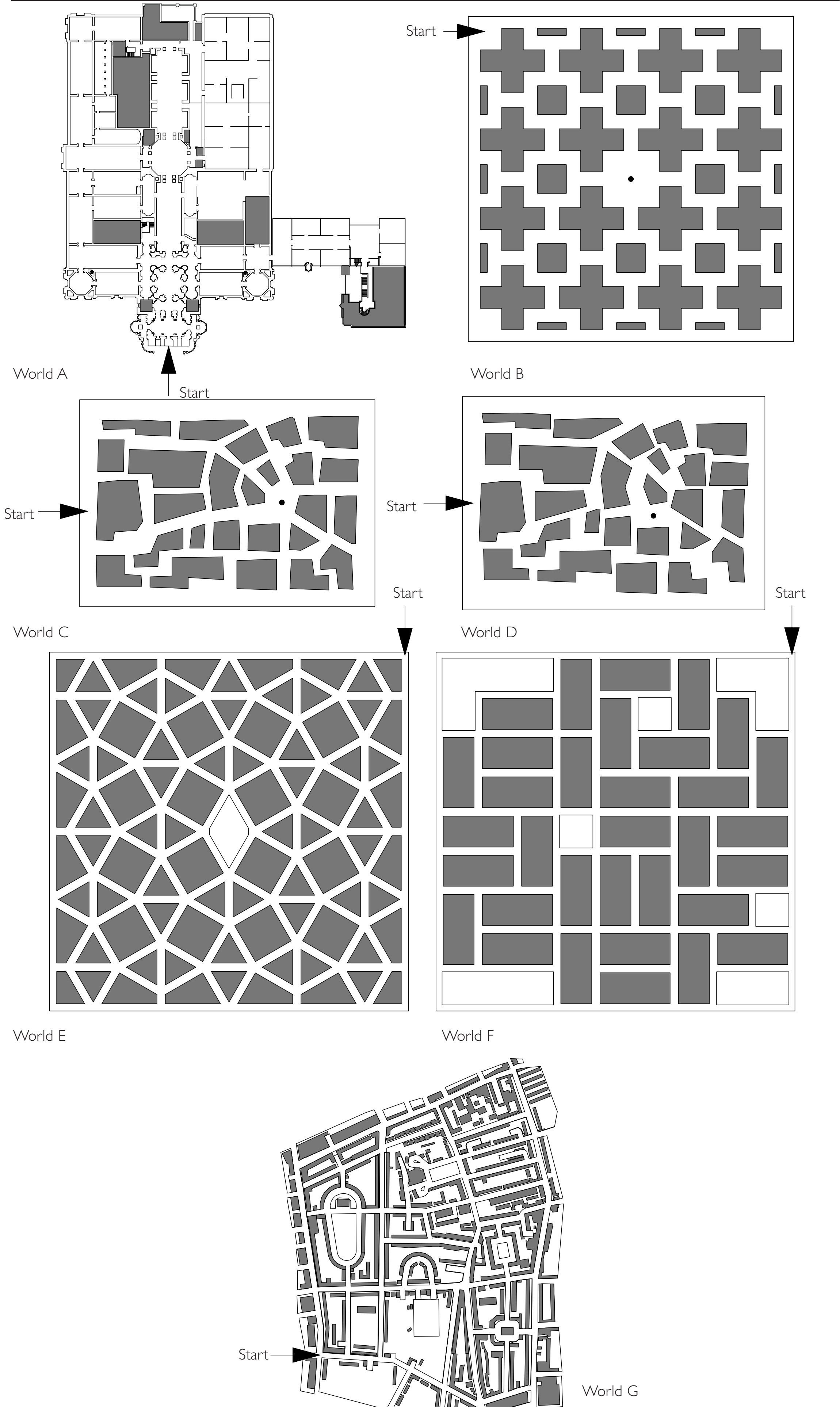


Figure 4.1 Plans of the Virtual Worlds

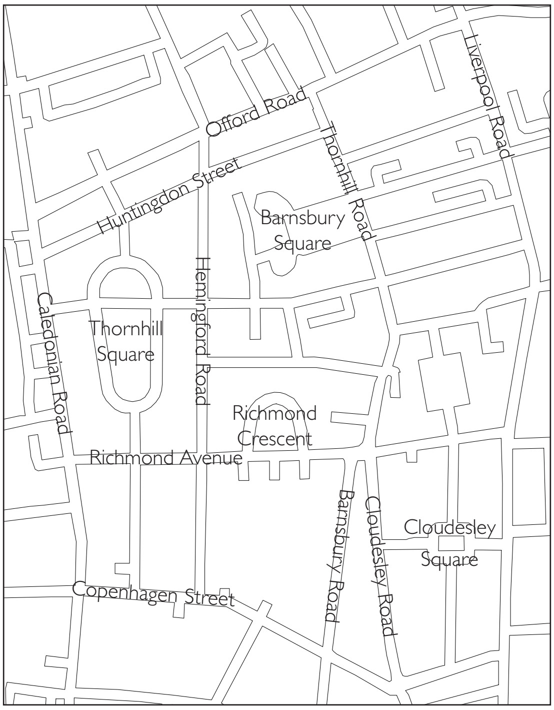


Figure 4.2 Street Names of Barnsbury

Subjects

World A

The subjects participating in the virtual Tate Gallery experiment are described in the previous chapter. Chapter 3.

World B

The subjects participating in this experiment were 36 unpaid volunteers all of whom were delegates attending a one day conference[3] entitled "Parallel Space: The Geography of Virtual Worlds", at the Institute of Contemporary Arts in London. The age range of the volunteers was 22 to 52 with a mean age of 33 years. Exactly one third of the volunteers were female. This experiment had a greater proportion of female subject-participation than any of the other six experiments. The subjects' occupations varied considerably, yet represented a certain creative and artistic bias (not a remarkable fact, considering the conference venue). The level of their experience of immersive virtual environments (also estimated by the volunteers on their questionnaire) ranged from no experience at all, to frequent experience and familiarity of such technology.

Worlds C – G

Thirty-one unpaid volunteers took part in this series of experiments. Every volunteer participated in each of the five experiments and hence navigated through all of the five test worlds in turn. The majority of the subjects (although not all) were postgraduate students of architecture from University College London or the Architectural Association School of Architecture. 67.7% of the subjects were male and 32.3% female. Although their experience of *immersive* virtual environments was quite limited, 41.9% of the sample had played computer games that require the user to navigate though a series of simulated environments, thus making this group one of the more sophisticated and less naïve of those that were used. The average age of these subjects was 28, with a maximum age of 40 and a minimum age of 23 years. The questionnaire that they were given at the end of the experiment can be found in Appendix C.

Experiment Procedure

The apparatus used in the experiments was identical to the set-up described in the previous chapter. However, the procedures for each wayfinding task varied depending on the environment in which the experiment was being conducted and on the wayfinding task set.

World B

In World B, the subjects were given a verbal description of the layout of the world (namely, that it was square in shape and that the subjects were entering the environment at one corner of the world). They were told that their task was to find a monument (they were also given a verbal description of the monument's appearance) which was located in the exact centre of the world. Subjects were informed that they were starting from one corner of the world and that the direction they would be facing at the beginning of the experiment would also be the direction of the monument. They were then instructed to find the monument and given no further assistance of any kind. There were no time constraints put upon this experiment.

Worlds C and D

Worlds C and D were presented as a pair of worlds, in which the same tasks, and hence the same instructions were given. The subjects all started in the same location, in both of these worlds. They were told that there was a monument in the exact centre of each of the two worlds (again, a verbal description of the monument's appearance was given) and that it was their task to find the monument in both worlds. They were informed that it was to be a timed task and that the experiment would end precisely after ten minutes whether they had found the monument or not. On entering the world, each subject was instructed to turn around until they were facing the direction of the monument (their visual field was constantly monitored on a second screen). On reaching the monument, in the first experiment (World C), the subjects were unexpectedly instructed to attempt to find their way back to the starting point by retracing their original route. In the second world (World D), the subjects obviously anticipated that they would be asked to perform the same route-retracing task, as indeed they were.

Worlds E and F

Worlds E and F were also treated as a pair of worlds with exactly the same task to be performed in each world. Again, there was a strict time constraint of ten minutes for each of these experiments. The subjects entered the world at one corner (the worlds both being square in plan) and facing towards the centre of the world. They were then instructed to attempt to cross from one corner to the diagonally opposite corner, approximating a diagonal route as closely as possible (i.e. going around the edges was discouraged). The experiment was terminated when the subjects reached the diagonally opposite corner (or the corner *assumed* by the subject to be the opposite corner). In the previous experiments (worlds A-D) subjects were constrained to the equivalent of a real-world walking speed (1.79ms^2). This had also been the intention for these experiments. However, due to occurrence of unforeseen events during the experiment procedure[4] a decision was taken to allow subjects to move at a faster speed in order to complete the experiments.

World G – Barnsbury

This experiment constituted the most complex wayfinding task of the series and was performed last. The test consisted of a wayfinding task in three parts; to navigate to location A, on reaching A to navigate to location B and then to C. In this experiment, rather than using a landmark such as a monument as a destination, the wayfinding goals were all urban spatial features (a square, a crescent and a keyhole shaped 'square'). Before the subjects started, they were shown a sketch of each of the three types of location, drawn to the same scale such that the relative sizes of the features were clear. Once they entered the virtual world, they were instructed to turn around until they faced in the direction of their first goal, goal A (the keyhole shaped square). They were then given no further instructions until they arrived at goal A (whilst being monitored closely on a second screen). On arrival at goal A, they were verbally reminded of which feature constituted goal B (the crescent). They were again instructed to turn around until they were facing in the direction of goal B. On arrival at goal B they were given a verbal reminder of goal C (the square), and once again were instructed to turn around until they were facing in the direction of goal C. If they reached goal C before the time limit expired, then the experiment was terminated at that point. If the subject had still failed to find some or all of the goals and the ten-minute time limit had been reached, then the experiment also ceased. This was the most detailed and complex of all the spatial navigation-tasks. As in worlds E and F, subjects were permitted to move at a faster rate (faster than walking speed) within this environment.

The Virtual Worlds

Each of the test-environments will be described in turn, concentrating initially on their formal and visual properties then presenting a variety of spatial descriptions/representations of each environment. At first, the spatial analyses of the environments are used to provide a comprehensive description of all aspects of the environments being used. Secondly, they are included to allow for an examination of the paths taken by the subjects in terms of the environments' spatial configuration as used currently by Space Syntax researchers. The examination of the paths will be presented at the end of this chapter alongside their visualisation.

Formal Layout & Design

All of the virtual worlds could be defined as 'large-scale' virtual environments, using both Darken and Sibert's or Kuipers and Levitt's definitions. In Darken and Sibert's definition they state that a virtual world may be held to be large-scale if "there is no vantage point from which the entire world can be seen in detail" Without question all of the seven virtual worlds used in this series of experiments fit into this category.

World B

The virtual environment in which the subjects were placed consisted of a simulated urban or suburban (it was deliberately ambiguous) development equivalent in area to a 'real world' square whose sides measured 236 metres. The area covered by the virtual world represented, therefore, a real world area of approximately 55,000m^2 or approximately 13.6 acres. All of the urban blocks forming the development comprised of varying arrangements of two

Figure 4.3 Screenshot of World B

storey, domestic dwellings, rendered with a high resolution texture map, a photograph of a real domestic building. Around the edge of the development the texture maps displayed a clear, visually identifiable, 'mixed-use' urban street, comprising of a variety of building types such as shops, offices, restaurants and public houses, as shown in figure 4.3. This visual distinction was intended to aid the subject by allowing clear identification of the development boundary, rendering it visually distinct from the central urban blocks. It was not possible for the subjects to move beyond the boundary of this 'urban street', nor was it possible to walk through any of the buildings. However, the subject could walk freely anywhere else in the world, both on the pavements and the roads, both of which were clearly identifiable and modelled to British urban planning guidelines. There was an open square in the centre of the development, which contained a 'green' with a monument at the centre. This monument resembled a generic sandstone cross (the wayfinding goal).

Figure 4.4 The Wayfnding Goal of World B

The spatial layout of the world was designed on a guiding principle that every line of sight be kept as short as possible, terminating at a building facade. Any long and penetrating lines of sight were excluded from this world, resulting in an environment that hindered the acquisition of global layout information from local cues. The resultant form in plan is somewhat maze-like, and a number of subjects responded that they found it both confusing and disorientating.

Worlds C and D

At first glance worlds C and D look very similar indeed. They are two fictional worlds, each containing the same shape and number of urban blocks.

Figure 4.5 Screenshot of World C

They are based upon a pair of theoretical examples by Hillier. Their street configuration is similar, however some of the blocks in 'World C', have been moved slightly in 'World D' significantly altering the spatial syntax of the whole world. The real world size-equivalent of the two worlds is 356 metres by 250 metres ('World C') and 365 metres by 258 metres ('World D'). Refer to pages 126-128 of *Space is the Machine* (Hillier 1996) for the first published reference to these two worlds.

All buildings are rendered using high-resolution textures. In these worlds, the building textures are photographs of a London Georgian House of 3/4 stories in height. Figure 4.4 shows the monument located at the centre of World D (the same monument was used for World C).

Figure 4.6 Screenshot of World D

Worlds E and F

Worlds E and F are also a pair of worlds both covering the same area, 650 x 650 metres. World E was designed with a guiding principle of using roads of equal lengths, joining at a variety of junctions. (One aim of this world was to create a diversity of junction types, whilst keep-

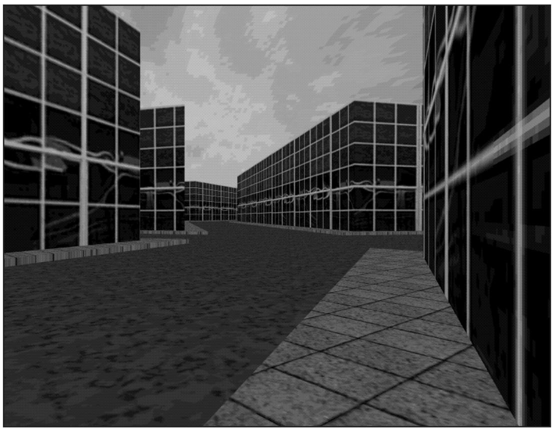


Figure 4.7 Screenshot of World E

ing road lengths a constant). Textures are used throughout for distance cueing. The textures used in these two environments are quite different to those used in worlds C and D, resembling instead a modern, glass office façade rather than a Georgian house.

In World E, there is an open space in the centre of the world, and a continuous boundary road at the world's perimeter. The urban blocks in world E are either squares or equilateral triangles of equal façade length. The same texture is used on both the boundary edge condition and on the central urban blocks.

World F is based upon an artificial street-plan from Hillier's book (Hillier 1996). This world contains urban blocks that are all double squares and are

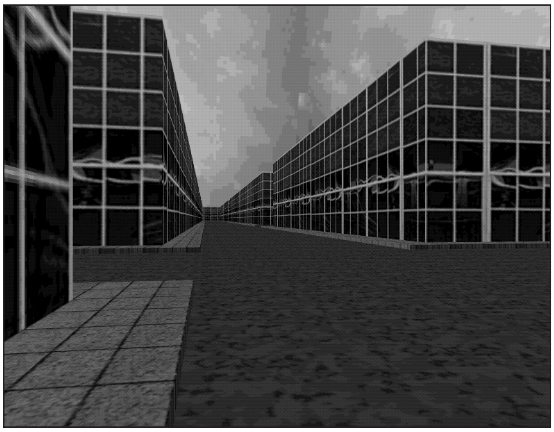


Figure 4.8 Screenshot of World F

placed to form random open areas. The edge condition or boundary is treated in the same manner as World E, with similar textures used and a road that runs around the perimeter of the world.

World G – Barnsbury

World G is a simulation of a real district of North London, Barnsbury, in the London Borough of Islington. Its area covers an approximate rectangle of 532.2 metres by 669.5 metres at its greatest extents. The real world district is bounded by Caledonian Road to the East, Liverpool Road to the West, Offord Road to the North and a combination of Copenhagen Street and Cloudesley Place to the South. The textures used on the buildings are not the actual textures of the real world buildings (since too many textures would have been required, causing memory problems for the

Figure 4.9 Screenshot of World G

virtual simulation). Instead, the texture used is the generic Georgian London 3/4 storey façade, as used in Worlds C and D.

Figure 4.1, illustrates the plans of all of the seven worlds (not drawn to an equivalent scale). The subjects' starting positions are indicated by arrows.

Axial Analysis, Global Integration

Figure 4.10 overleaf illustrates the patterns of global integration resulting from axial analyses of these worlds. This is a form of analysis performed by taking the fewest and longest lines of sight, such that they pass through every convex space in a system (see Chapter 1, for a fuller description). The integration patterns formed by this analysis are calculated by constructing a graph representation of the relationships between these lines of sight. Where any two lines cross, this is represented by a link (or edge) in the graph, the lines being represented by nodes. The global integration value of a line is then determined by analysing the shape of the graph as seen from that line. It is a measure of how far (in terms of the number of changes of direction rather than metric distance) a line is, on average, from every other line in the system. Red represents a smaller distance; i.e. a line of sight that is highly accessible from all other lines in the world, and hence is termed a highly *integrated* line. Blue represents a larger distance, i.e. a line that is extremely inaccessible from all other lines in the system. This is termed highly *segregated*. The spectrum between the two extremes runs as follows, red, orange, yellow, green and blue. This colouring convention is used throughout this thesis. This method of analysis was first developed by Hillier and his colleagues at University College London, and forms a component of a larger family of analytic methods termed Space Syntax.

World B and World E

The four axial lines constituting the external boundary of World B are the most integrated in this world. The most segregated lines are those which fall between the boundary and the centre of the world (the wayfinding goal). The lines at the very centre of the world are relatively well integrated (albeit less so than the outer boundary). This pattern of integration is mirrored in World E, which also has a highly integrated outer boundary and relatively integrated centre. However, the integration core at the centre of World E is more distinct and easily discernible than in World B. Like World B, the more segregated parts of this World E are also those which lie between the centre and the outer edge.

Worlds A, C, D and F

These worlds can all be characterised by the fact that they all contain a single primary integrating axial line. In World A, The Tate Galley, the most integrating line is the main axis of the building (running vertically up the page on plan), which leads from the main entrance, dividing the building

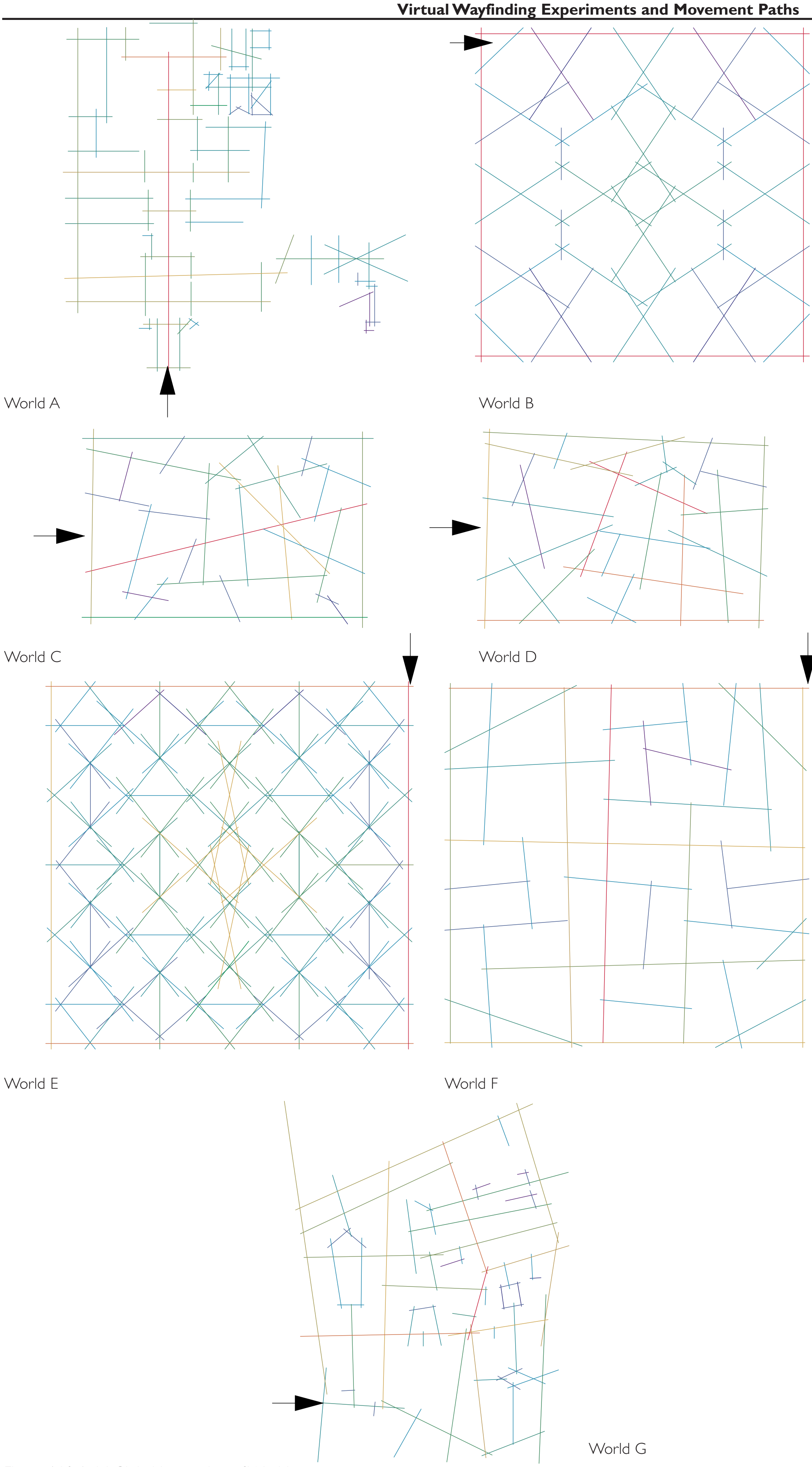


Figure 4.10 Axial Global Integration of Worlds

in two. This main axis is crossed at right angles by secondary, integrating lines. The most segregated part of World A, is the Clore Gallery, located in the bottom rightmost side of the plan. The other section of the gallery that is relatively segregated is the 'Pay-per-view' area in the top right hand corner of the plan.

World C, which is one of a pair of very similar worlds, can be distinguished from its partner world by means of its single, integrating axial line. This line starts close to the subjects' starting position and then passes through the main square (the wayfinding goal). Three of the four most integrated lines in this world happen to pass through the open 'square' at its centre.

World F also has a primary integrating axial line, which runs from top to bottom on plan. This line is crossed at right angles by relatively integrated lines, some of which constitute the boundary roads.

World D is the partner world to World C. Whereas World C contained a single integrating line that traversed the length of the entire world (diagonally from left to right). World D contains a number of highly integrated lines near the main 'square'. Unlike World C, none of these integrating lines of sight actually pass through the main open space (which is also the location of the wayfinding goal). The boundary roads in World D are more integrated than the equivalent roads in World C.

World G

World G or Barnsbury, has an integrated core focussed around a short, yet strategic road, the small diagonal road to the centre right of the plan (part of Thornhill Road). A cross of relatively integrated roads is formed by the roads Richmond Avenue and Hemingford Road, to the left of Thornhill Road. Pockets of segregated areas are distributed around this district with various squares in this area proving to be quite segregated and it is some of these, which were selected to be the wayfinding goals in this experiment.

Axial Analysis, Local Integration

Local integration is calculated in a similar way to global integration in all respects bar one. The local integration value of a line considers only those lines of sight that are a specific distance (in the graph) from the line when calculating its value. All other lines that exceed the specified distance (in terms of changes of direction or links in the graph) from a line are simply discounted. The method of visual representation of these two measures is very similar. The axial lines are coloured according to their local integration value. Red lines are locally integrated and blue lines are locally segregated. The usual distance, or radius, used to calculate local integration is three (three changes of direction, three steps away). This is the radius used in the following analysis.

Worlds A B and C

In Worlds A B and C the pattern of local integration mirrors that of global integration for these worlds. In World B, the boundary lines are the strongest local integrators. In World A, the Tate Gallery, the most locally integrated line remains the primary axis through the centre of the building and the Clore Gallery (to the bottom, rightmost side of the plan) continues to be relatively segregated. In World A there are more pockets of segregation at the local level than were evident at the global level. In World C, the pattern of local integration appears to be extremely similar to that of global integration.

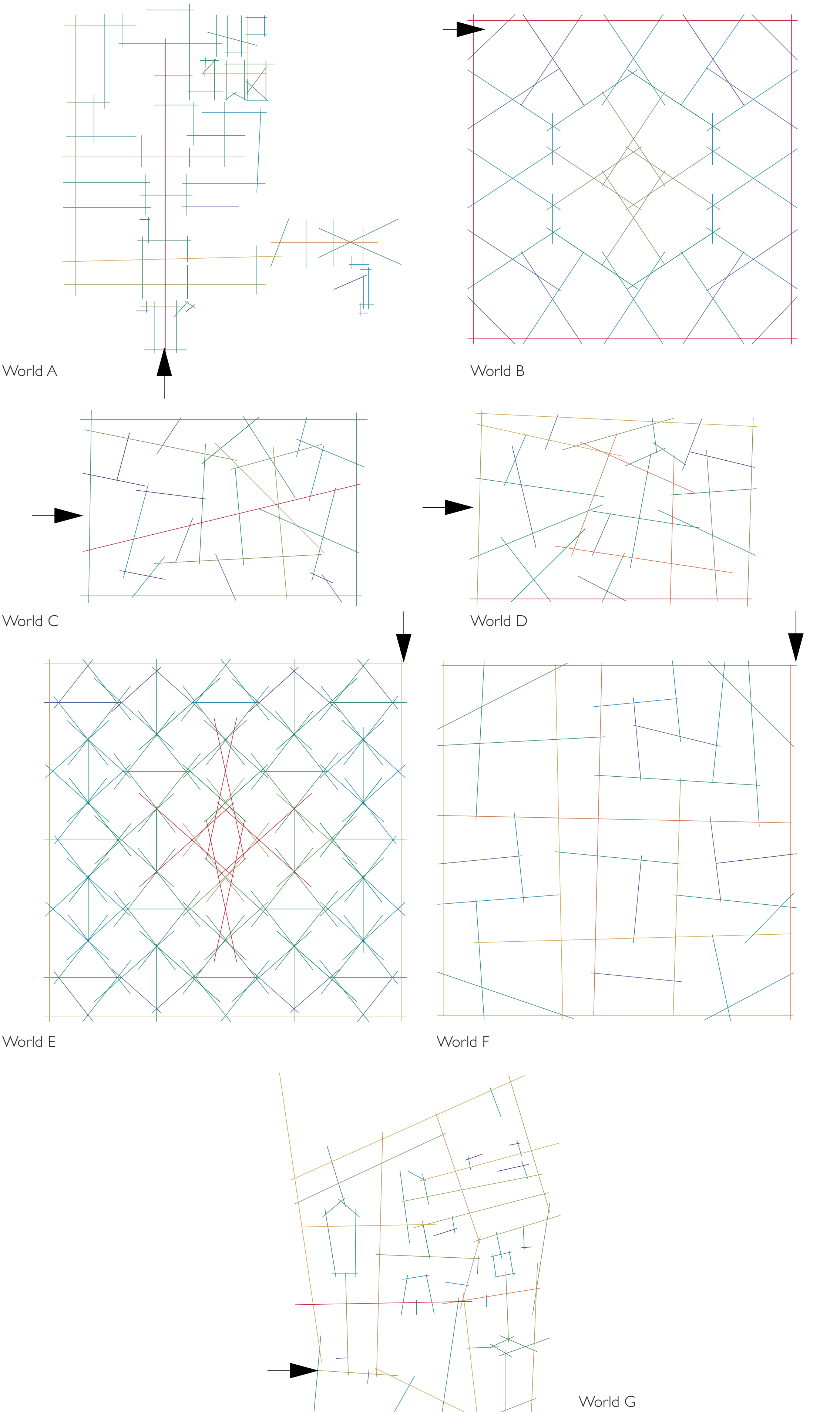


Figure 4.11 Axial Local Integration of Worlds

World E

The world whose local integration pattern differs most from its pattern of global integration is World E. World E had a globally integrated boundary, with a less globally integrated centre. In terms of local integration, it has a striking, locally integrated core at the centre of the world and its boundary becomes far less important at the local level.

Worlds D F and G

Worlds D F and G, neither mimic their patterns of global integration so closely as worlds A B and C. Neither do they differ so radically from their patterns of global integration as World E. These three worlds produce local integration patterns which are similar to the results of their global integration analysis, with the exception that the most integrated lines have shifted slightly. Lines that were secondary integrators at the global level have become primary integrators at the local level.

In World D, the most integrated lines have shifted to the bottom (on plan) of the boundary lines. The groups of lines that were the most globally integrated are still high local integrators; they are no longer the most integrated lines in the system. In World F, as in World D, the most locally integrated line becomes one of the boundary roads (the uppermost on plan) with the globally integrating lines becoming less significant at the local level.

In World G, or Barnsbury, the pattern of global and local integration also differs. Globally the most integrated line was the small diagonal line to the centre of the area (part of Thornhill Road). This line is no longer the most integrating at the local scale; instead, it is the horizontal road that passes through the centre of the district (Richmond Avenue). In all of these last three worlds, D F and G, the patterns of segregation remain consistent.

Axial Analysis, Point Depth

The measure of point depth of an axial line is simply a description of the depth of the graph from a single point. In this particular case, the point from which the graph's depth is calculated is the starting point, where the subjects entered the world. This point is marked by an arrow on plan. Those lines coloured red are the closest to the starting position and those that are blue are the furthest away (in graph terms). In the particular case of these experiments, the colours represent the numbers of turns or changes of direction necessary to get from the starting point to any other point in the world. For example, the dark blue lines represent those parts of the world that would require the greatest number of changes in direction to reach. Since subsequent work (See Chapter 6) suggests that people are inclined to make as few changes in direction as possible, the dark blue areas represent the most inaccessible areas of the graph (from that specific starting point).

Worlds B and E

Worlds B and E are particularly interesting, since the centres of both the worlds are the greatest distance (not metric distance, but distance in the graph) from their respective starting positions. In World B, the wayfinding goal was the centre of the world. Hence, the subjects were attempting to find a location that was furthest away (in graph terms) from their starting point. In World E, the subjects were aiming to get from one side of the world to the diagonally opposite corner. They were instructed

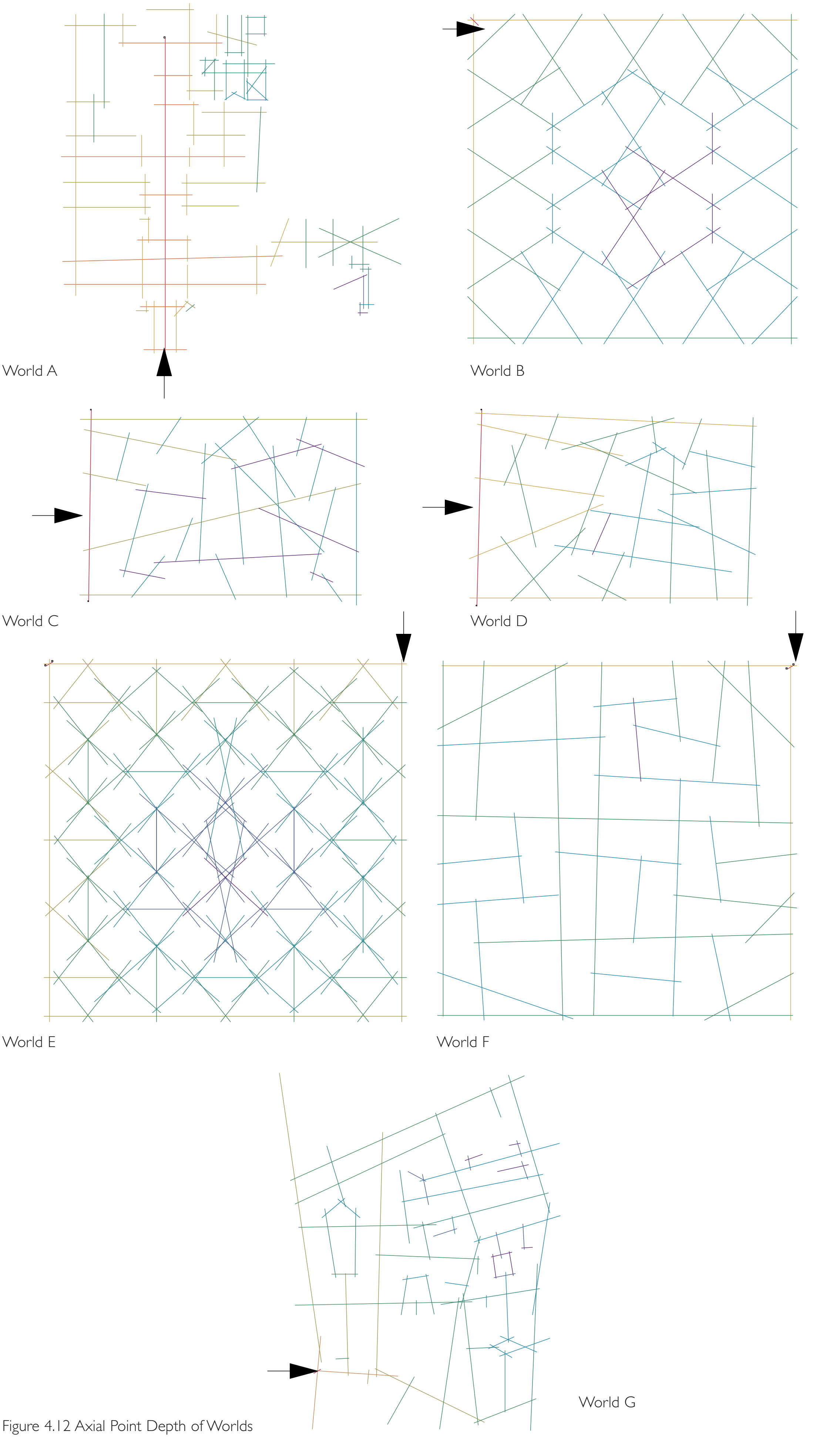


Figure 4.12 Axial Point Depth of Worlds

not to go around the edge of the world, but to attempt to take a diagonal course (which would take the subject through the 'bluest' areas). In the light of this analysis, it is perhaps not surprising that even after being instructed not to go around the edge of the world, that many subjects did travel along the boundary roads. This strategy makes absolute sense when viewed in conjunction with point depth analysis. See figure 4.16 for route paths.

World A

In World A, the section of the world which is furthest from the entry space is the Clore Gallery (on the bottom right of the plan). The second furthest area (in graph terms) of the building is the 'Pay-per-view' gallery in the top rightmost corner. Since the navigational task for the Tate Gallery was one of *exploration* rather than a wayfinding task of any kind, then any relationship between point depth and the wayfinding goal can have no bearing in this world (because there was no goal).

Worlds C and D

Worlds C and D produce particularly interesting point depth analysis results. Essentially these two worlds are almost identical, with the same number of buildings in approximately the same locations. The difference between these worlds is that in World D, several of the buildings have been moved by relatively small amounts, however the spatial result of this action is quite remarkable. Although it appears that World C has more lines that are dark blue, in fact these lines are only three steps away from the starting point, i.e. to get from the starting position to any of these blue lines requires only three changes of direction. In contrast, to get from the starting point in World D to its most segregated lines would require *four* changes in direction. The graph of the world, as seen from the starting point of World C is 75% shallower than that of World D. One interpretation of this fact is that everywhere in World C is more accessible from the subjects' starting location than World D.

Worlds F and G

World F bears similarities to many of the other worlds. Like Worlds B and E, the outer boundary is very near (on the graph) to the starting point. From the starting point of World F, the whole world is quite accessible, or appears quite shallow in graph terms.

The analysis of World G or Barnsbury is quite enlightening. The wayfinding task for this world was an informed, staged search, with three separate wayfinding goals. The first two goals, Thornhill Square/Crescent and Richmond Crescent are both three steps away. The third goal, Lonsdale Square is the dark blue square to the middle right of the plan. It is interesting to note that few subjects managed to locate this final square.

All Line Axial Analysis

All line axial analysis is performed by generating every line of sight that connects a corner of a building to every other visible corner of the buildings in the vicinity. It is then necessary to extend each such line (in both directions) until its ends terminate at the façade of another building or buildings. In this manner, instead of the fewest and longest lines that pass through any space, there are multiple lines of sight passing through every convex space. This method of analysis clearly does not produce *all* available lines of sight, since that number would be not to go around the edge of the world, but to attempt to take a diagonal course (which would take the subject through the ‘bluest’ areas). In the light of this analysis, it is perhaps not surprising that even after being instructed not to go around the edge of the world, that many subjects did travel along the boundary roads. This strategy makes absolute sense when viewed in conjunction with point depth analysis. See figure 4.16 for route paths.

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Worlds C and D

Worlds C and D produce particularly interesting point depth analysis results. Essentially these two worlds are almost identical, with the same number of buildings in approximately the same locations. The difference between these worlds is that in World D, several of the buildings have been moved by relatively small amounts, however the spatial result of this action is quite remarkable. Although it appears that World C has more lines that are dark blue, in fact these lines are only three steps away from the starting point, i.e. to get from the starting position to any of these blue lines requires only three changes of direction. In contrast, to get from the starting point in World D to its most segregated lines would require *four* changes in direction. The graph of the world, as seen from the starting point of World C is 75% shallower than that of World D. One interpretation of this fact is that everywhere in World C is more accessible from the subjects’ starting location than World D.

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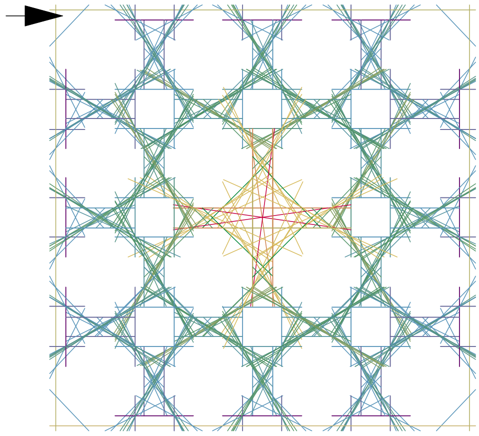
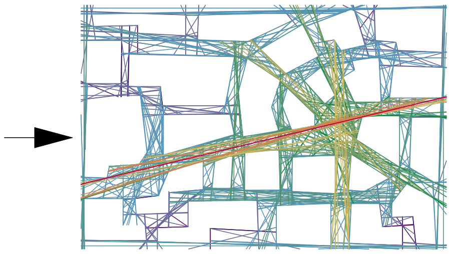
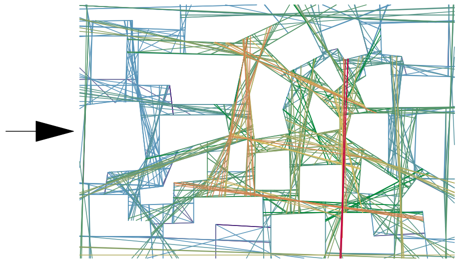


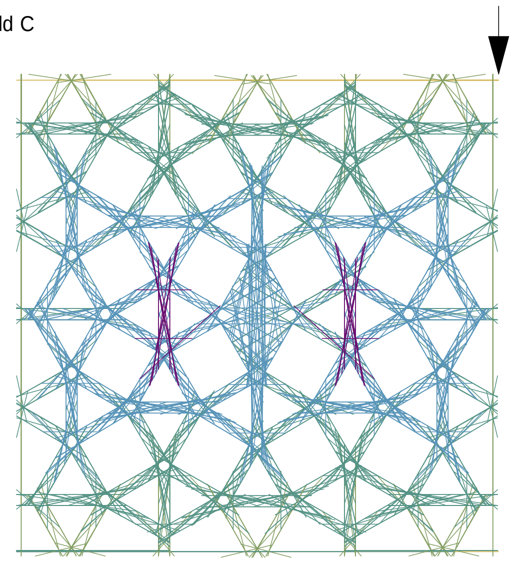
World B



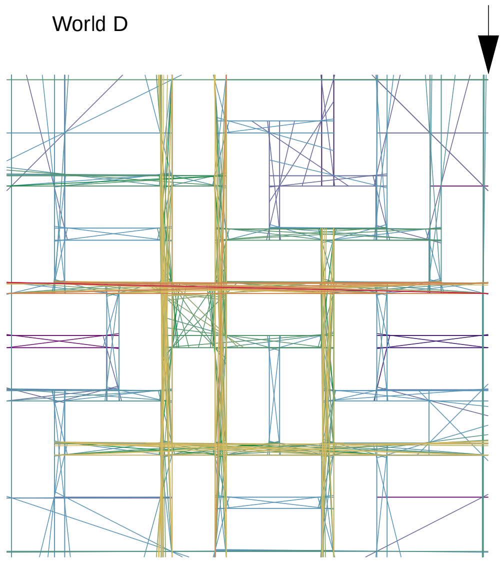
World C



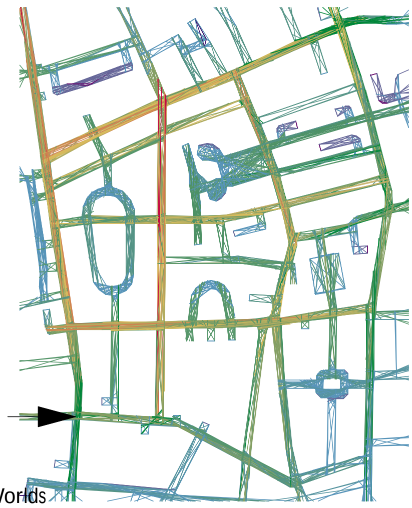
World D



World E



World F



World G

Figure 4.13 All Line Axial Integration of Worlds infinite. However, it could be held that the lines so calculated are the *more* strategic lines of sight in a world. Axial lines can therefore be seen to be a sub-set of the set of all line axial lines. The integration values for all line analysis are calculated in exactly the same manner as for normal axial analysis. The analysis illustrated in figure 4.10 shows global integration values for the seven worlds. This form of analysis was not performed on World A (the Tate Gallery), due to the complexity of the plan of this world.

World B and E

World B and World E are interesting, since their local and global axial analyses followed quite similar patterns. For each world, the boundary lines were highly integrated, followed by a secondary integration core at the centre of each world. This characteristic was less predominant for global integration and more marked for local integration. The central core was more distinct in World E than in World B. However, for all line axial analysis this pattern is completely reversed. World B can be seen to contain a quite striking integration core at the centre of the world (where the wayfinding goal was located). However, in World E, the centre of the world becomes relatively segregated in complete contrast to its global and local axial analyses.

Worlds C, D and F

The all line axial analysis of Worlds C and D mimics their patterns of local and global axial integration quite closely. The integration pattern for the all line analysis of World C is, in particular, quite striking.

The results of the all line axial analysis of World F are quite similar to its patterns of local and global axial integration, with the same streets emerging as primary integrators in all three types of analysis. In the axial analyses, however, the most integrated line is the rightmost of the two longest vertical lines (as seen on plan) whereas for the all line analysis, the major integrator becomes the single horizontal line (as seen on plan).

World G

Perhaps the world that differs most in terms of its all line analysis when compared to its axial analysis is World G or Barnsbury. Here the pattern of integration has shifted entirely to the uppermost section of Caledonian Road and Hemingford Road (the two vertical roads to the left of the plan). This is quite a different pattern when compared to the results of the axial analyses, where the integration core focussed around Thornhill Road and Richmond Avenue.

Convex Space Analysis

Convex space analysis is performed by breaking-up all navigable space into the largest and 'fattest' (or those with the greatest area to perimeter ratio) convex spaces, such that all space in the world is expressed as a convex space. The term convexity, in this context, indicates a state of mutual visibility from any point in a space to every other point occupying that same space. If this condition can not be met, the space can not be described as convex. The relationships between these spaces are then analysed by constructing a graph-representation of their relationships in a manner identical to axial analysis. Each convex space is represented as a node in the graph, and the connections between spaces (or whether it is possible to move directly from one space to another) are translated into the links (or

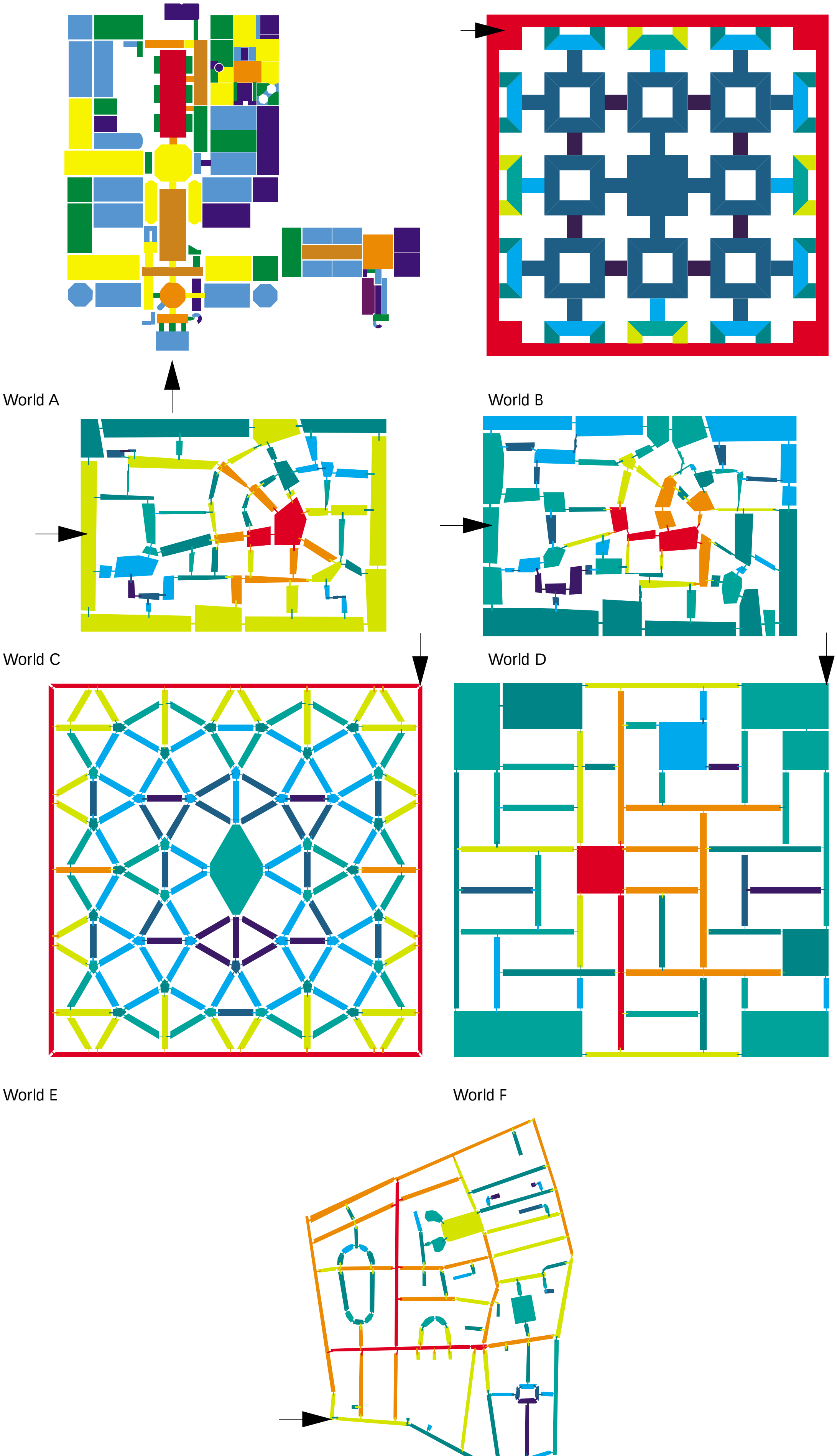


Figure 4.14 Convex Space Analysis of Worlds

edges) in the graph. The colours indicate the global integration values for the convex spaces.

Worlds B, E and F

Worlds B and E both have highly integrated outer boundaries, with their centres being quite segregated. This is the opposite of World F, where the centrally situated open square is most integrated space in the system.

Worlds C and D

Worlds C and D bear a similarity to World F, in that a large, central open square is the most integrated space (as opposed to a line of sight) in the world. It is particularly interesting to note that in these two worlds, the most integrated space is actually the 'square' that contains the wayfinding goal (a market cross).

World A

World A, or the Tate Gallery, is still dominated spatially by the central axis running vertically on plan. Since, in this analysis, the central axis is subdivided into a number of convex spaces, we can see that the integration has shifted to the uppermost part of the central space. Other, secondary, isolated pockets of integration include the Clore Gallery (to the bottom right of the plan) and the 'Pay-per-view' section, or the top rightmost corner of the plan. The galleries to the far right of the central axis are also quite segregated.

World G

In World G, the pattern of integration of the convex spaces produces a 'cross' of integration being formed by two roads, those of Hemingford Road and Richmond Avenue (slightly to the left of the plan). Roads that were shown to be highly integrated in the axial analysis are still proving to be highly integrated using convex space analysis.

Overlapping Convex Space Analysis

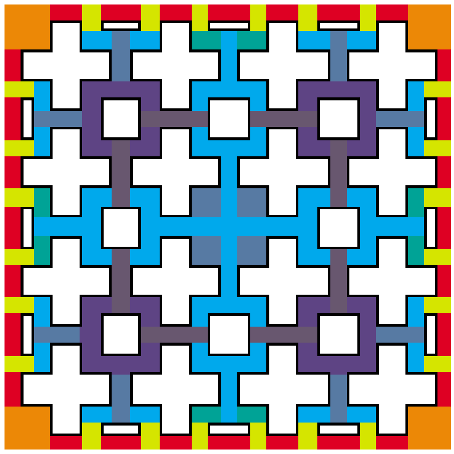
This analysis is performed by automatically generating the set of all possible convex spaces in a world. Spaces are then represented as nodes in a graph and if any two convex spaces overlap, then this relationship is represented as a link (or edge) in the graph. In this way, a graph representation can be constructed of the entire system. The colours are identical to the colour spectrum used for global integration with red being the most integrated and blue the most segregated convex spaces.

World B

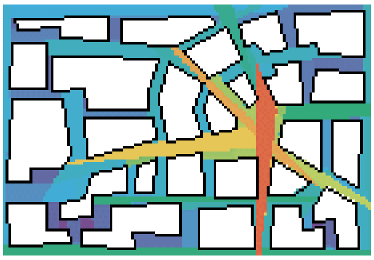
At first glance, World B stands out from all the others, due to the relative uniformity of its integration values. The range of values is certainly small, however the external boundary is slightly more integrated than the rest of the world.

Worlds C and D

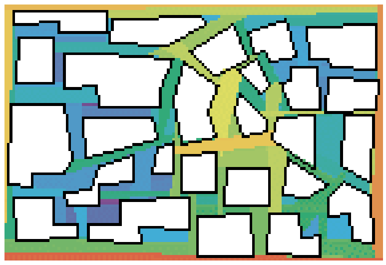
The analyses of Worlds C and D, the pair of worlds, are interesting because of their differences. For World C the most integrated spaces are those passing through the centre of the world where the wayfinding goal is located. This echoes the results of the axial analyses, the all line axial analysis and the convex space analysis. The most integrating overlapping convex spaces of World D, on the other hand, are located at the boundary of the world. Although the spaces surrounding the wayfinding goal, at the centre of World D, are still relatively integrated compared to the rest of the world, this pattern is not as marked as World C.



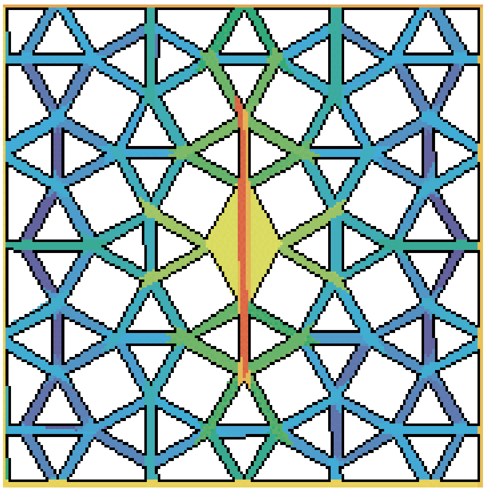
World B



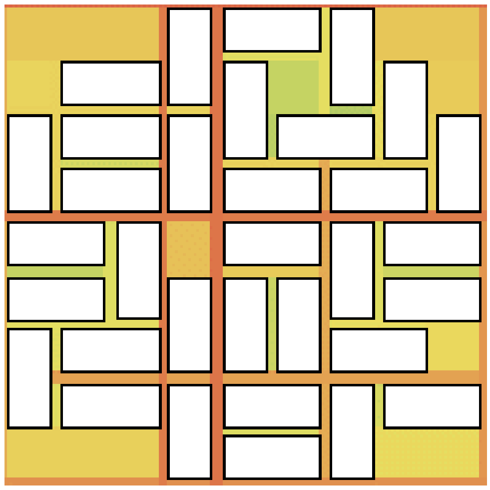
World C



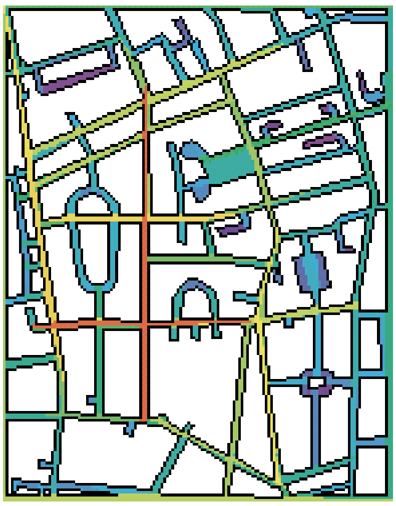
World D



World E



World F



World G

Figure 4.15 Overlapping Convex Spaces

World F

World F, can be held to be quite similar to World B, for the reason that its range of values is rather limited (although not as limited as World F). The three spaces that emerge as being the primary integrators are in fact the three axial lines that are prominent in the axial line, all line and convex space analyses.

World E

The analysis of World E reveals a single primary integrating convex space passing through the centre of the world running vertically from top to bottom (on plan). The boundary spaces are also quite integrated, with pockets of segregated spaces located between the edge and the centre. These results have more in common with the axial analyses of this world (both global and local integration patterns) than with the all line or convex space analyses.

World G

The overlapping convex space analysis of this world identifies two streets as the primary integrators, Hemingford Road and Richmond Avenue, forming a cross to the bottom right of the centre of the world. This result has more in common with the convex space analysis of the same world than with any of the axial measures (although many of these featured Richmond Avenue, the horizontal road, as being strategically integrated). The patterns of segregation are quite similar to the areas of segregation performed by the other forms of analysis. Again, this method of analysis was not performed on World A, the Tate Gallery, due to the complexity of its plan.

Paths of Subjects

The following diagrams presented in figure 4.16 illustrate all paths taken by the subjects in all the worlds. These were the first visualisations made after transforming the raw output data into 2d CAD format. (See Chapter 3 for further information on how the paths were produced). The results for each of the worlds are discussed below with reference to the previous spatial analyses of the environments. To understand the relationship between space and movement at an aggregate or cumulative level is a necessary first stage before further investigating which small-scale actions may have contributed to the creation of these observed patterns.

World A

All subjects began their exploration of the Tate Gallery at the main entrance, or the centre-bottom on plan. It can be seen that the central axis of the building featured strongly in many of the routes taken by the subjects. If the number of paths along the central axis can be compared to paths following the equally long axial line that runs up the far left of the plan, it is clear that the central axis has more ‘traffic’. In the axial analyses of world A, the main axis is the most integrated line in the building and the left-most vertical axis is an extremely strong local-integrator. Three horizontal cross-routes prove to be quite popular, the lowest of these leads to the Clore Galley. The least explored areas were the right-most rooms located between the Clore Gallery and the ‘Pay-per-view’ area; these areas were the most ‘segregated’ in terms of both axial and convex space analyses. Therefore, this pattern of space-use appears to mirror all syntactical analyses precisely. The results from the different methods of analysis indicate that the two vertical axes were consistently

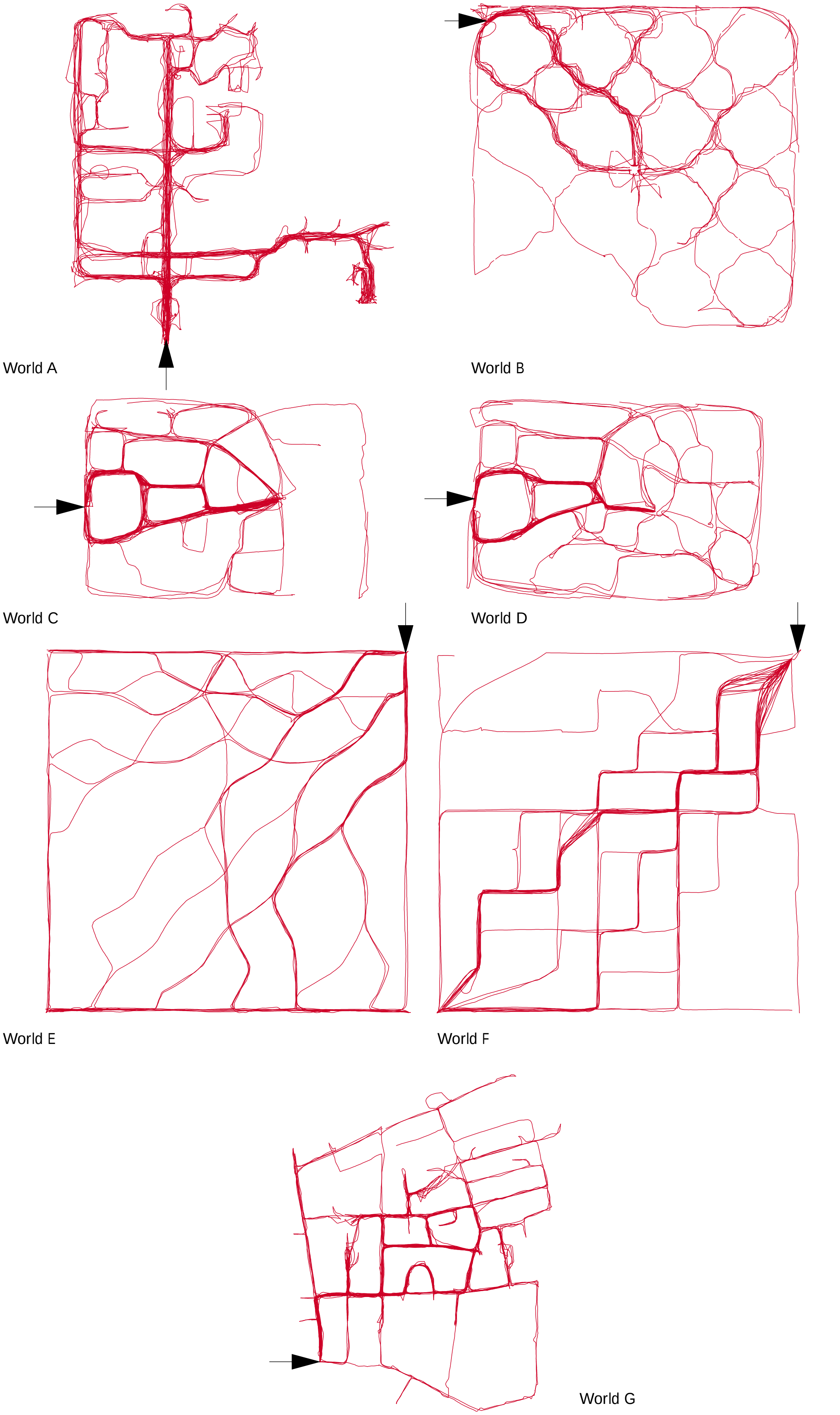


Figure 4.16 Cumulative Paths of the Subjects in the Worlds

integrated (and highly populated) as were a number of the cross-axes. In contrast, the Clore and 'Pay-per-view' galleries were under-populated as well as being segregated areas when analysed. Overall, there is a significant left-hand bias to the movement within the building, with some spaces to the right of the building on plan never being visited at all. This pattern is consistent with all of the configurational analyses applied to this building.

World B

In World B, the subjects all began in the top left hand corner (on plan) and were aiming for the centre of the world. It can be seen that two routes emerge as being the most popular routes to the centre, these being the most direct diagonal paths which could have been taken. The leftmost path (considered from the starting point of the subjects when facing towards the centre) is more popular than the rightmost path, a pattern that is mimicked by all the paths. More people turned to their left immediately after entering this world, than did to their right. On entering the world 70.00% of subjects turned initially to their left. This left-hand bias is clearly reflected in the overall paths too, with one half of the world more 'travelled' than the other half. The majority of subjects can be seen to have reached the centre. In terms of the spatial analyses of this world, it can be seen that the outer roads are the primary integrators whilst the wayfinding-goal is located in the most segregated space in the world, the centre. It could be suggested that this makes the task all the more difficult and may explain why those subjects who failed to find the straightest route to the centre became extremely lost (the task is, in Space Syntax terms, counter-intuitive).

Worlds C and D

Worlds C and D were the pair of worlds. The subjects started in the same location in both of these worlds, the middle of the leftmost side. They began by facing the centre of the world, and were all aiming for the same location in both worlds. After reaching the centre, they were then asked to retrace their steps. In World C, one route emerges are predominant. It appears to be irrelevant whether or not a subject initially turned to their left or to their right (64.52% to their left, 35.48% to their right), since after negotiating their away around the first urban block, the majority of subjects then take the same route to the centre. This most-popular route is the most integrated axial line in this environment. In contrast to this, in World D, it is much harder to identify any single route as being preferential. In addition to this, many more subjects appeared to get 'lost' after reaching the central square and attempting to return to their starting point. This may be accounted for by the fact that the central square is relatively segregated in World D unlike World C. Since subjects are attempting to find their way back to the starting point from a fairly segregated location, it is no surprise that a number of them get lost. This behaviour can be seen quite clearly by the fact that the movement traces of World C are mostly confined to the leftmost side of the world, whereas there appears to be little difference between the number of movement traces on the left and right sides of World D (as seen on plan). Subjects get lost in World D because it is an unintelligible environment, whereas they do not get lost in World C as it is far more intelligible[5]. The effect of the difference in the intelligibility of these two environments is clearly reflected in the two sets of movement paths. This result is all the more powerful when it is considered that these different spatial configurations were caused by a minor displacement of a few of the buildings and yet the affect on movement was considerable.

Worlds E

In Worlds E and F, the wayfinding task given was identical. The subjects entered the worlds in the top rightmost corner; they were instructed to make their way across the world to the opposite diagonal corner. In World E, a few subjects managed to pick an almost perfect diagonal route through the world, however many subjects appear to begin traversing this diagonal then take a 'wrong turn' at some point and to suddenly 'lose their bearing'. A proportion of the subjects appeared to spend a period of time during which they navigated around the edge of the world although they were instructed not to do so. Their disorientation was also made clear by the fact that many subjects actually navigated to the wrong corner and yet when prompted, responded that they thought they were at the correct corner. The temptation to navigate around the edge of this world was particularly strong, as the boundary roads are such good integrators in this environment. On examination of the plan view of this environment (see figure 4.1) it is easy to pick-out 'near diagonal' routes that appear to meander across the world. It is these meandering routes that the subjects were expected to take. However, no such routes emerge when performing spatial analyses of this environment. This is because there are no long lines of sight linking across this world and hence what appears to be a viable route on plan is not evident as such on the ground.

World F

In contrast to World E, in World F, many more subjects appear to be able to find a quite efficient diagonal route to the opposite corner despite the irregularity of the grid. Very few subjects in this case resorted to navigating around the edge. Almost all subjects made it to the correct corner. There is no single route which emerges as being a favoured route, however certain roads had quite high levels of traffic, including the primary horizontal road which emerged as being particularly integrated for the all line axial analysis. It is extremely clear that for this world the most popular routes also followed the most integrated axial lines. In summary, it is hypothesised that the majority of subjects partially followed the major integrating axial-lines that form a cross in the centre of the world, connecting centre to edge. It is further suggested that due to this property, these roads could be used by the subjects to orient themselves within the environment. This is why they found it easier to reach the opposite corner in this world compared to the previous one. This is another example of an intelligible grid allowing effective movement in contrast to an unintelligible grid (World E) resulting in confusion and disorientation.

World G

The subjects entered Barnsbury at the bottom leftmost corner, or the corner of Caledonian Road and Copenhagen Street. No particular routes emerge as being popular, and there was a greater diversity of routes for this world than for any other, however this may well be due to the nature of the three-goal wayfinding task that was presented to the subjects. Two roads emerge as being quite popular, these being Richmond Avenue and Hemingford Road, again two roads which emerged as being quite integrated in many of the methods of analysis described in earlier sections of this chapter.

It is clear that by examining the patterns of virtual navigation and comparing the most popular or well-frequented routes to patterns of spatial-integration (using a number of methods of analyses), that cumulative movement appears to mirror patterns of integration. This appears to be true for all of the seven test environments. It should be stressed that this is not a statistical observation, rather it is an attempt to judge 'by eye' which routes are the most popular and then to compare this judgement to the results of the spatial analyses.

The primary aim of this thesis is to investigate which small-scale actions may produce the aggregate patterns of movement such as those presented in the latter half of this chapter. With this question in mind, the most striking result is found when comparing the 'pairs' of worlds (Worlds C & D and Worlds E & F). For each pair, the intelligible world appears to facilitate movement that is efficient (i.e. they are reaching their goal) in comparison to movement in the unintelligible world in which a high proportion of subjects appear to become lost and disoriented. Since the definition of intelligibility concerns the relationship between the local visual cues (e.g. connectivity of a line) and the global properties of a space within a system, this result implies that subjects are correctly reading and interpreting the local visual cues available. In the intelligible worlds (where the relationship between local and global properties of space is strong), this relationship allows subjects to navigate efficiently (which they are being seen to do). In the unintelligible worlds, this approach fails to assist them, as the relationship between the local and the global is less strong, even misleading. In these worlds, they become lost. The interpretation that this allows (with reference to how small-scale actions produce aggregate patterns of movement) is that it may be said that in an intelligible environment, by noting and acting upon local visual cues, overall patterns of movement may emerge which correlate with configurational analyses of space. Another conclusion that may be drawn from this chapter is that we appear to make use of local, visual cues in a virtual world in a manner similar to our behaviour in the real world.

A secondary research-question that this thesis is concerned with is whether virtual environments *can* be used to investigate this relationship (namely between small-scale and large-scale, between local and global). Although this approach was initially supported by a pilot study presented in the previous chapter, the results of this chapter also help to validate this method. Since the work of Space Syntax researchers over the years has yielded strong correlations between pedestrian movement and patterns of integration and this relationship appears to have been reproduced by these experiments then it may be assumed that these results can be used to investigate the relationship between local behaviours/decisions and the emergent phenomenon which is pedestrian movement.

Finally, it should be noted that the conclusions drawn from these results have arisen from a series of judgements about which routes appeared the most popular. Since this is a common technique that may provide useful information about the manner in which space is being used, it seems that there might be a need to accurately compare a group of paths to determine the most popular. A method to enable the comparison of a sample of routes will be developed in the following chapter, Chapter 5.

Left or Right-hand Bias

The final section of this chapter is included to briefly investigate an apparent pattern observed in the paths of the worlds, which appeared to demonstrate a certain handed-ness. Particularly in the case of World B, it appeared that most people, after entering the world, turned initially to their left. In order to determine whether this was actually occurring, the table below presents an analysis of the initial decisions made by subjects in the world. On entering the world, the first change of direction of a subject is noted. The results are as follows.

World	% Turning Left	% Turning Right
World A	45.83%	54.17%
World B	70.00%	30.00%
World C	64.52%	35.48%
World D	51.61%	48.39%
World E	56.67%	43.33%
World F	54.84%	45.16%
World G	88.46%	11.54%

Table 4.2 Left and Right Hand Bias of Subjects' Decisions

Although, the original intuition in World B is supported, as 70% of all subjects began their journey by turning to their left, this bias is not supported elsewhere. The only other World, which shows a high proportion of subjects turning one way or another, is World G, or Barnsbury. However, on entering this world, the subjects were verbally instructed to turn around until they were facing in the direction of the first wayfinding goal. The direction of the first goal from the starting position would have orientated the subjects slightly to their left, and therefore it is not at all surprising that the majority of the subjects (88.46%) actually turned to their left. On dismissing this world from the sample, it can only be concluded that no such bias is evident from this sample of seven worlds. Therefore, it is unlikely that the left-hand bias of World B can be of any significance.

Conclusions

This chapter began by introducing the visual, formal and spatial characteristics of the seven test worlds used as the empirical basis for this thesis. The equipment and apparatus for the experiments were described in Chapter 3. It is hoped that these experiments were described in sufficient detail to render them reproducible by others were the need to arise.

This chapter concluded by presenting the basic visualisations of the paths that the subjects took through each of the seven test worlds (including World A). It was noted that the majority of subjects appeared to be moving in a manner highly consistent with Space Syntax patterns of integration. This observation was made by scrutinising the movement data and then by attempting to gauge the routes through the world that had been the most popular. The integration values of portions of these popular routes were then noted. On the whole, these heavily used routes were highly integrated within the system, when analysed using Space Syntax techniques. This chapter concluded by noting that it would be extremely useful to be able to accurately calculate the most popular routes from a sample of routes. Therefore, the following chapter of this thesis will present a method of determining the most common routes by applying a technique known as 'string-matching'.

Key Points

- The types of world that can be used in such experiments can be either simulations of real buildings or urban environments or entirely fictitious, theoretical worlds.
- Even from the pure routes paths alone, i.e. prior to additional analysis, the route data can be extremely informative about how people were using space.
- At first glance people appear to be moving in a manner that is very 'syntactic', that is to say consistent with patterns of integration.
- Subjects appear to make use of local, visual cues in a similar manner to our behaviour in the real world.
- There is a need to be able to calculate more accurately the most popular routes from a sample of individual routes.

Notes

[1] The definition of an intelligible environment is given on page 129 of Space is the Machine Hillier, B. (1996). Space is the Machine. London, Cambridge University Press. where it says that "The property of 'intelligibility'… means the degree to which what we can see from the spaces that make up the system - that is how many other spaces are connected to - is a good guide to what we cannot see, that is the integration of each space into the system as a whole. An intelligible system is one in which well-connected spaces also tend to be well-integrated spaces. An unintelligible system is one where well-connected spaces are not well integrated, so that what we can see of their connections misleads us about the status of that space in the system as a whole."

[2] This number includes the Tate Gallery experiment.

[3] The date of the conference was the 5th July 1997.

[4] An unusually high proportion of subjects experiencing dizziness and nausea.

[5] Refer to footnote number 1 at the beginning of this chapter.

Chapter Five:
Applying String-matching Techniques to Spatial Decision Analysis

Abstract

This chapter presents a technique for analysing route choice decisions made in a test environment. This method of analysis is based upon the assignment of a unique, identifying ASCII character to specific, key spaces or locations in the environment. Each route can then be represented as a character string constructed from the sequence of key spaces or locations through which the subject has passed during the experiment. The character string of each route can then be compared to every other character string in the observation sample using a string-matching algorithm. A measure of 'distance' between any pair of strings can then be determined, this being the minimum number of transformations required to change one string (or route) into another. The output data from this series of experiments are presented as example applications of this string-matching methodology, and the results of the spatial decision analysis calculated. The outcome of applying such a technique to these experiments suggests that it could be a useful analytic tool for determining the popularity of any individual route or for selecting routes which can be held to be suitably representative of a sample of routes. The chapter concludes by noting that the most popular routes in the samples appear to be the straightest, an observation that would not have been made were it not for the use of the string matching techniques developed in this chapter.

Introduction

This chapter is partly methodological. That is to say, it starts by introducing a novel application of a technique already used in other academic fields. It uses the procedure known as string matching and applies it to an architectural, spatial problem and through doing so creates a necessary modification of the original algorithm. It is essential that the first half of this chapter should explain the application of this method in full, in order to be able to use it at the end of this chapter to analyse the routes generated in the previous chapter, Chapter 4. Through the analysis of the routes, this chapter starts to investigate how small-scale actions result in overall patterns of pedestrian movement by taking a 'top-down' approach, namely starting with whole routes. The new method of analysis that is developed in this chapter is being used to seek patterns within a sample of different routes. The search for patterns is central to understanding movement as an emergent phenomenon, as it is the overall patterns that characterise it as such. Equally the search for patterns in the routes is necessary to begin to explore which small-scale actions may result in the aggregate patterns of pedestrian movement. The method will, at the end of the chapter, be applied to all movement data and may reveal interesting patterns inherent in the data.

It was noted in the previous chapter that it would be extremely useful to have techniques for the categorisation of routes taken by subjects through an environment. Such 'movement traces', or visual representations of paths taken by individuals through environments have been used extensively by Space Syntax researchers (see Chapter 1 for more information regarding observation methods). Yet methods for assessing such data are limited to specific quantitative techniques, such as 'gate counts', namely a calculation of the mean flow of pedestrians through certain key 'gates' or thresholds as defined on plan. Another quantitative method often used is the calculation of the total number of persons occupying a pre-defined space (such as a room) during a precise time period. However, resulting quantitative measures such as mean flow or occupancy rates are attribute characteristics of the sample as a whole. There are, as yet, no useful techniques for comparing a single route to any other route or to a set of routes in a *qualitative* manner. The measure presented in this chapter, 'mean, normalised Levenshtein distance[1]', does appear to achieve this goal, in that it provides researchers with a tool for measuring any route against either another single route or against the larger sample of all observed routes. Another way of interpreting this technique is that it facilitates a measure of the aggregate decisions taken by a subject, since mean, normalised Levenshtein distance enables the comparison of a unique set of spatial decisions to a second unique set. Mean, normalised Levenshtein distance can therefore be held to be a 'similarity measure', gauging how *similar* a route is to all other routes in a sample. It is for this reason that it can serve to be an extremely useful technique for the selection of a *representative* route or routes, if a smaller sub-sample is required.

This chapter describes an application of 'string-matching' or 'string editing' techniques to the analysis of a sample of observed pedestrian routes through an environment (real or virtual), to determine a single, unique measure. This calculation can then be used to identify the most frequently chosen routes in the sample, the most idiosyncratic routes in the set of all observed routes and then to be able to grade all other routes between these two extremes using sliding scale of values.

Method of Analysis

Representing a Route as a Character String

Imagine that the leftmost diagram of figure 5.1 represents the plan of a building. This building contains sixteen cellular rooms, with a single door located in each of the four walls of every room. Some of these doors lead to adjacent rooms, and some to the outside of the building. To enable the representation of any route through this building as a character string, *one* method that can be used is to assign a distinct ASCII[2] character to each room in the building, for example the room in the top left hand corner of the plan has been labelled 'A'. The result of labelling all rooms in this fashion is a series of spaces labelled A through to P as illustrated in figure 5.1 below.

Each individual space must be assigned a *unique* character. Using this technique rooms or spaces can be assigned *any* of the available ASCII characters, excluding white space but including both upper and lower case letters of the alphabet and all standard punctuation characters. This permits a total of 94 characters for assignment.

Imagine once more that two subjects are required to start in room A and make their way to room P. The first subject moves from room A to room B then to rooms F, J, N and O, finally ending up in room P. The route that this subject has taken may therefore be represented by the character string 'ABFJNOP'. The 'movement trace' of this route is marked on the middle diagram of figure 5.1. The second subject takes a near identical route but decides to pass through room K as an alternative to room N (as taken by the first subject). The character string 'ABFJKOP' can therefore be used to describe the route of the second subject and the movement trace of this route is marked on the rightmost diagram of figure 5.1.

If we compare these two strings ABFJNOP and ABFJKOP, we can note some basic facts about them. They are both character strings of the same length (seven characters long) and are almost identical (in terms of the spaces the subjects walked through). If we wished to transform ABFJNOP into ABFJKOP, we would need only to substitute the letter N in the first string for the letter K in the second string. This act of substitution represents a real-world action, the second subject choosing to walk through room K instead of room N. Since only a single transformation is required to change the first string into the second we can say that the 'distance' or 'metric distance[3]' between these two strings is 1.

Figure 5.1 Principals of Representing a Route as a String

More specifically, since this technique will be developed to use the Wagner-Fischer algorithm[4] later in this chapter, it can also be stated that the 'Levenshtein distance' is also 1 in this case. This is a very simple example and the calculations are more complex for longer strings of varying length, but the basic principle remains identical to this straightforward example.

ASCII Assignment and Spatial Measures

Note that in the example above, *rooms* were used as the basic unit for assigning ASCII text identifiers. However, the example of the building that contained only sixteen square rooms was such an elementary environment that each room could clearly be assigned a single character. In some buildings or urban environments, the layout is sufficiently complex that a simple spatial definition such as 'room' might be neither obvious nor appropriate.

There are, in fact, a range of possible spatial definitions that could be used for this process of ASCII assignment, such as rooms, convex spaces, axial lines/segments, junctions (which feature predominantly in the following chapter, Chapter 6), thresholds, or 'gates'. The use of 'gates' is essentially the process of defining a series of 'barriers' at strategic points on plan, such that when a person passes through this barrier or 'gate' this act is registered (as used to perform the real and virtual movement comparison in Chapter 3). These barriers need not be physical realities in the environment, but are purely devices used by the observer when collecting data (Vaughan, Major et al. 1997). A route can therefore also be defined by virtue of the series of 'gates' through which a subject passes from the beginning of the journey to the end of it. These gates could even be thresholds, or doorways.

The problem of selecting a suitable spatial unit with which to assign characters in an environment may be influenced not only by the complexity of the environment but also by additional methods of analysis to be applied at a later stage. For example, if gate count data is available for an area, then thresholds or 'gates' might be the most suitable choice for generating the strings. If mean room occupancy rates were being measured, then the use of rooms would lend itself to this method. Alternatively if junctions are a key part of the analysis, as in the following chapter, Chapter 6, where each junction in the world is being assigned as ASCII text character in order to determine what kind of decisions are being made at each junction, then it could be beneficial to use the same assignments for the route similarity measures too. To summarise, this technique is flexible enough to be adapted to every situation.

In every environment or experiment, it may be that there is one particular spatial sub-division or unit, that is more suited to the task of string-matching when compared to other spatial entities. Therefore, the first stage of applying this method involves making a judgement about *which type* of spatial unit to use. In the second half of this chapter examples are presented that are derived from each of seven virtual environments. Using these worlds, a range of spatial descriptions is used for calculating the route-strings.

Optimising the Assignment of the Unique Identifiers

Certain environments may potentially contain a large[5] number of rooms or spaces (or whatever spatial sub-division is to be used as the basic unit for assignment). Since this could cause the processing time for the string-matching algorithm to be increased as well as the ease of generating the route-strings to be decreased, then keeping the number of defined locations to a minimum could be beneficial. The next section of this chapter puts forwards some suggestions for how to reduce the number of spaces selected, in order to optimise the process of translating routes into character strings. This task can usefully be considered to be the identification of 'key' spaces or locations in an environment. The selection of these spaces should attempt to keep to a minimum the total number of key spaces chosen, yet be sufficient in number that every route can be uniquely identified by means of the spaces through which the subject passes.

This chapter does not attempt to prescribe standardised methods for identifying these key spaces but will instead attempt to present a guide to their selection; rules of thumb as opposed to rigid rules. The identification of these spaces is, however, key to a successful application of the string-matching method. The choice of key location can be likened to the selection of a 'resolution' for the analysis. Too fine a resolution (more spaces selected than necessary) may result in patterns of space use being missed and the selection of too coarse a resolution (fewer spaces chosen than required to describe the system in its entirety) may result in dissimilar routes being calculated as being more similar to one another than they are in reality. Once this method or other methods of key space identification have been applied, then it may be necessary to consider ways of eliminating spaces such that as few characters as possible (to reduce processing time) can uniquely identify each route. One technique for eliminating spaces is the consideration of which spaces may be held to be 'implicit' in a route.

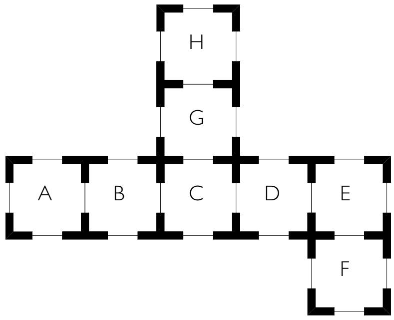


Figure 5.2 Redundancy in ASCII Unique Identifiers for Space Allocation

For example in considering figure 5.2 (again a set of cellular rooms similar to figure 5.1.) the *key* spaces could be taken to be spaces A, H and F, since all of the other rooms can be implied. For example, if it is known that a subject passes from room A through to room F, it is further known that their full journey must have consisted of A-B-C-D-E-F or A(B-C-D-E)F, since the spaces B-E are implied (it is not possible to get from A to F *without* passing through these spaces). In this example, the exclusion of the rooms B, C, D, E and G from the list of key rooms or spaces can be regarded as the identification and dispensation of the natural redundancy within the system. In graph theoretic terms the above example is equivalent to looking for chains in graphs and replacing them with a single node, an example of the graph process known as 'elementary contraction' (Jungnickel 1994).

Example of the String-matching Method

Figure 5.3 overleaf shows a selection of key spaces in the analysis of the simulated environment World C. For a more detailed description of World C, see Chapter 4. This example uses convex spaces located at road junctions for ASCII assignment. Note the use of both upper and lower case letters.

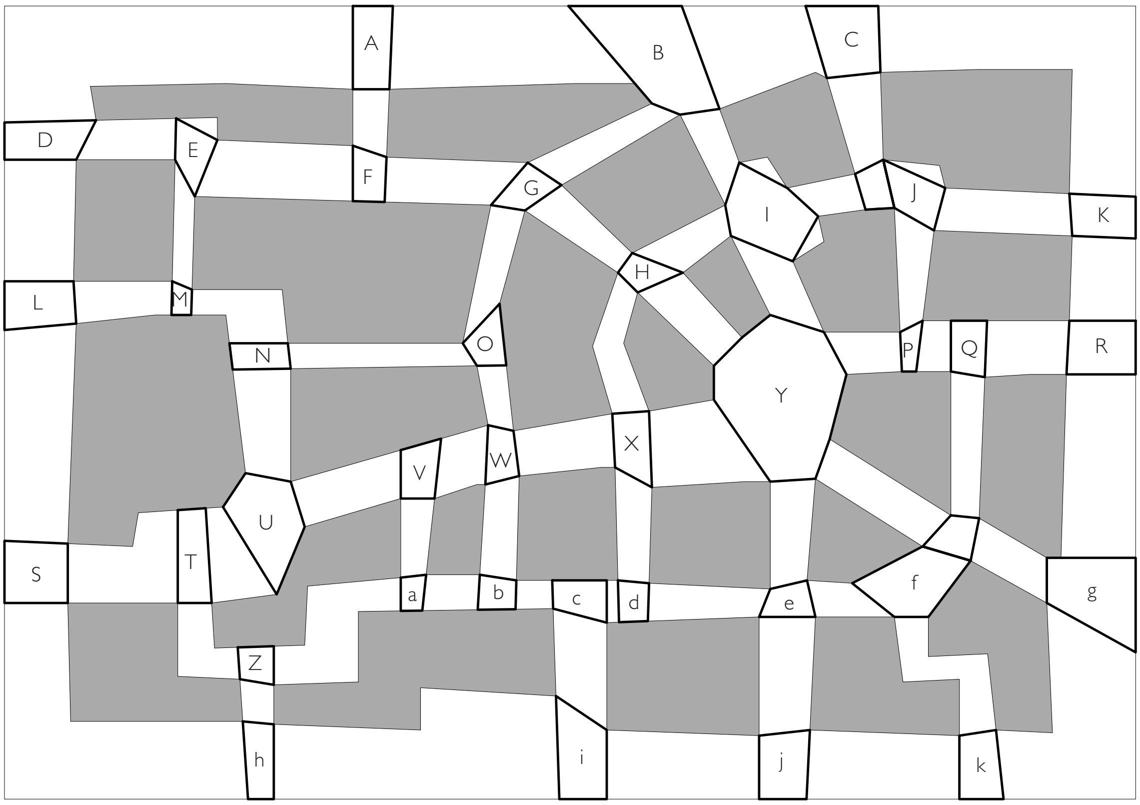


Figure 5.3 Allocation of Unique ASCII Identifiers in World C

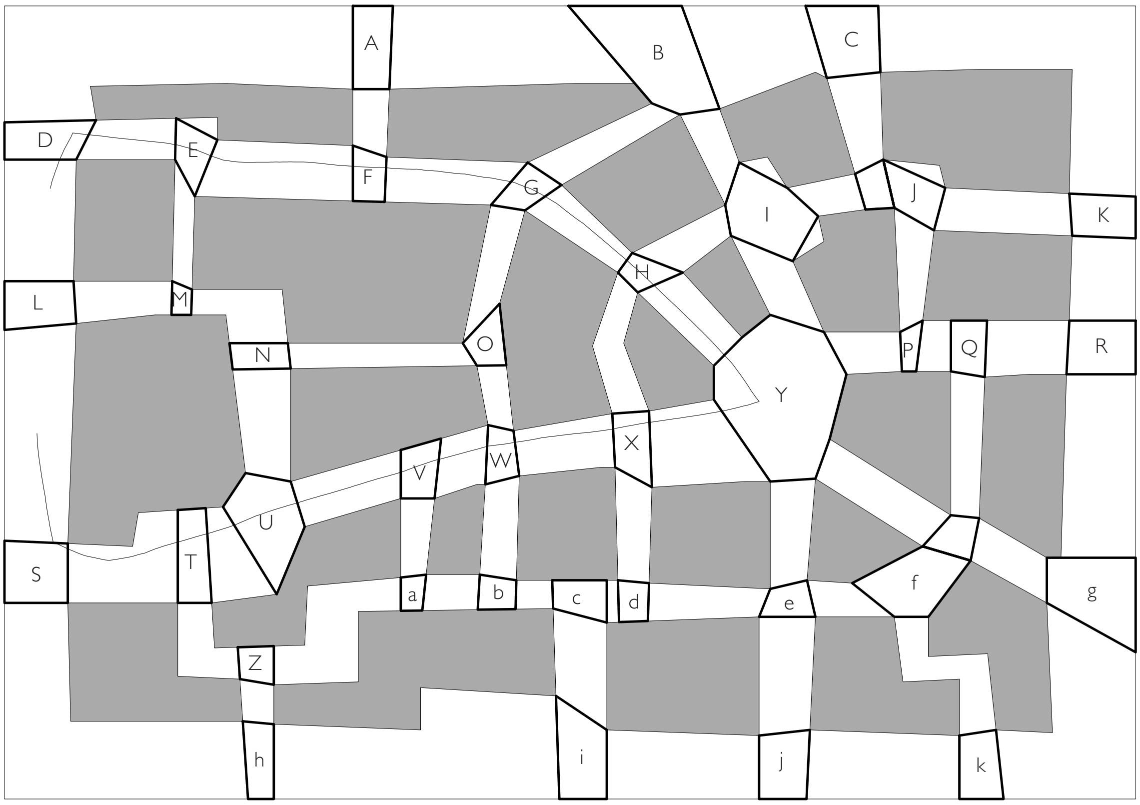


Figure 5.4 Example Route through World C

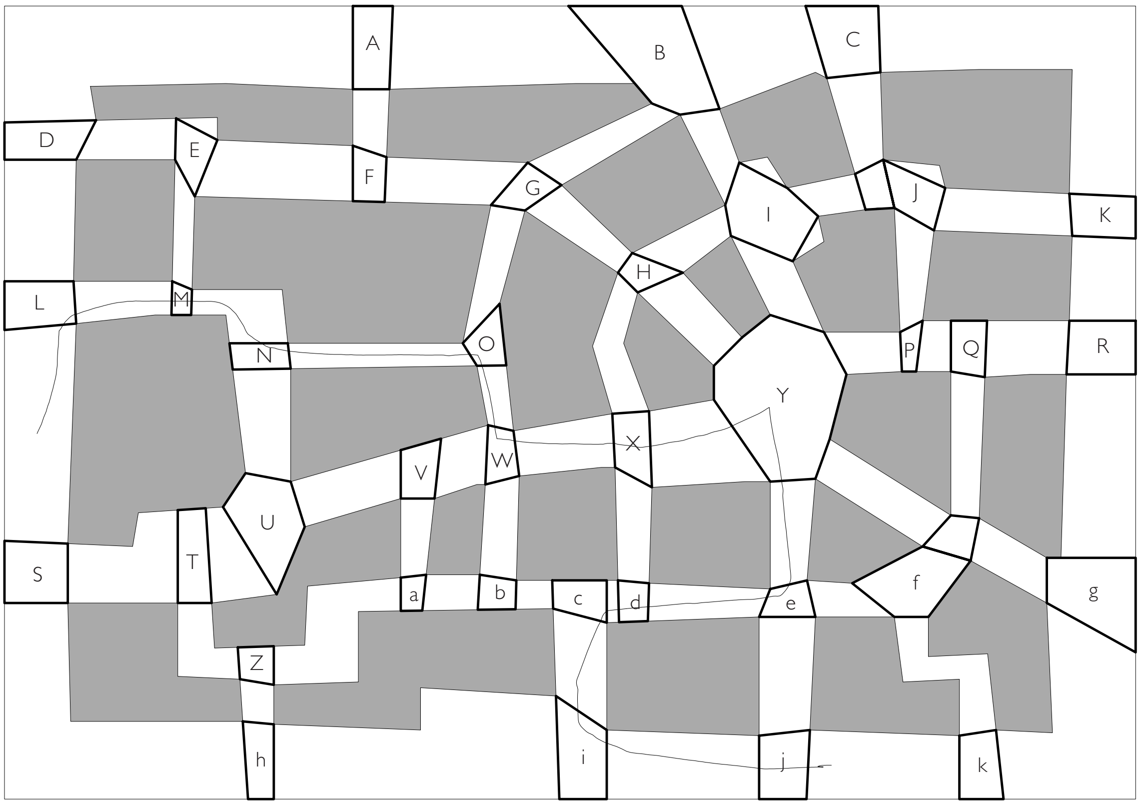


Figure 5.5 Example Route through World C

Figure 5.4 and 5.5 overleaf and above show the supposition of two actual routes taken by subjects onto the plan showing the key spaces of the environment. These assignments are then used to transform these pictorial routes into character strings. The route in figure 5.4 overleaf may be expressed as the following text string S-T-U-V-W-X-Y-H-G-F-E-D. The route in figure 5.5 above may be expressed as the following text string L-M-N-O-W-X-Y-e-d-c-i-j

The String-matching Algorithm

The use of string-matching techniques or the 'calculation of a metric distance' as a similarity measure between two character strings is used in many fields of research such as the comparison of genetic sequences, or for seeking similarities between eye path scans, see (Choi, Mosley et al. 1995).

The basic principle of any string-matching technique is to determine how many operations are needed to transform one string into another. In string-matching terms these operations can be of three kinds, the substitution of one character for an alternative character, the deletion of a character from either of the two strings or finally, the insertion of a character into a string. Obviously these operations differ slightly, for example the deletion of a character followed by the insertion of an alternative character into the same position in a string is equivalent to a single substitution of one character for a second. It is for this reason that insertion and deletion operations are known collectively as 'indels' (IN-sertions & DEL-etionS = INDELS) and *may* be treated differently to substitution operations (depending on the string-matching algorithm being used). The 'Hamming[6]' distance only allows for substitution operations and can only be applied to strings of equal length. For this reason, it was considered to be an unsuitable algorithm to be applied to route analysis.

One of the distinguishing characteristics differentiating methods of string-matching is the 'weight' attributed to the different operations (substitutions and indels). The algorithm proposed in this chapter weights all operations equally and can be applied to strings of equal or differing length. The number of operations required to transform one string to another is known as the Levenshtein distance (Levenshtein, 1965). It is worth noting however, that when using alternative methods, which weight a single substitution as being equal to an insertion followed by a deletion, then the distance calculated is known as the 'edit distance'.

In choosing which method to use, for there are many methods and algorithms for string-matching, we need to ask the following question, are the strings to be compared likely to be of differing length? Since it is most likely that this would be the case if applying this technique to the analysis of routes through environments, then the Wagner-Fisher algorithm, calculating the Levenshtein distance is probably the best algorithm to use. The one disadvantage of this method is that it does not take into account the occurrence of mirrored strings. For example, if there are two strings ABCDE and EDCBA representing two routes, then clearly if drawn onto a map, these would represent identical routes, with only their origin and destinations reversed. This reversal would not be picked up by the algorithm, as it would treat them as if they were quite distinct.

The Wagner-Fisher algorithm (1974) employs dynamic programming methods to calculate the Levenshtein distance between any pair of strings. It uses an iterative process to find successive distances between increasingly longer pairs of prefixes[7] of the two strings, computed with the use of a matrix. For example if we have two strings ABABA and AABBA, this algorithm would first calculate the distance, d, between A and A (d=0), then A and AA (d=1), between A and AB (d=1) and AB and AA (d=1) etc. with each subsequent calculation building upon the results of previous calculations until the distance between the two entire strings has been computed.

The equations for reproducing this method are given below. Let the two character strings for comparison be, x and y respectively. The length of any prefix of x is denoted as i and the length of any prefix of y is j. The metric distance, d, between these two prefixes is $d_{i,j}$ such that,

$$d_{i,j} = d\big(x(1,i), y(1,j)\big)$$

Equation 5.1

The next four equations prescribe the weightings for the various operations. Let w be the weight, which since we are using 'Levenshtein distance' then w must always be either 1 or 0 in value. a and b denote any single ASCII character in strings x and y, and ε represents a null character or white space. The entire set of weightings can therefore be described as follows,

$$w(a,\varepsilon) = 1$$

Equation 5.2

This means the weight of replacing character *a* by nothing, i.e. deleting *a* is 1.

$$w(\varepsilon, b) = 1$$

Equation 5.3

This means the weight of replacing nothing by a character *b*, i.e. inserting *b* into a string, is 1.

$$w(a,b) = 1 \;\; if \;\; a \neq b$$

Equation 5.4

This means the weight of replacing a by b, i.e. of substituting b for a is 1 (N.B. if 'edit distance' is to be used instead of 'Levenshtein distance', then this value is 2 instead of 1).

$$w(a,b) = 0 \;\; otherwise$$

Equation 5.5

This means that if character *a* is identical to character *b*, the weight is 0.

A matrix must then constructed, the parameters for this matrix being *(m+1)* and *(n+1)* where *m* and *n* are the lengths of the two strings *x* and *y*. The metric distance between each successive pair of prefixes (lengths, *i* and *j*) is then calculated and inserted into the appropriate part of the matrix. This process uses the following iterative or recursive function.

$$d_{i,j} = min \begin{Bmatrix} d_{(i-1),j} + w(x_i, \varepsilon), d_{i,(j-1)} \\ +w(\varepsilon, y_j), d_{(i-1),(j-1)} \\ +w(x_i, y_j) \end{Bmatrix}$$

Equation 5.6

Finally if the information regarding the upper and lower boundary conditions of the matrix are added to this function, then the formula can be represented in this way.

$$d_{0,0} = 0$$

$$d_{i,0} = \sum_{k=1}^{i} w(x_i, \varepsilon) \; for \; 1 \leq i \leq m$$

$$d_{0,j} = \sum_{k=1}^{j} w(\varepsilon, j_k) \; for \; 1 \leq j \leq n$$

Equation 5.7

To illustrate the use of this algorithm, two route strings, each representing a separate route, are taken from 'World C' and presented overleaf as an example. These strings are 'S-T-U-V-W-X-Y-H-G-F-E-D' and 'L-M-N-O-W-X-Y-e-d-c-i-j' and represent the routes already illustrated in figures 5.4 and 5.5.

	S	*T*	*U*	*V*	*W*	*X*	*Y*	*H*	*G*	*F*	*E*	*D*
L	1	2	3	4	5	6	7	8	9	10	11	12
M	2	2	3	4	5	6	7	8	9	10	11	12
N	3	3	3	4	5	6	7	8	9	10	11	12
O	4	4	4	4	5	6	7	8	9	10	11	12
W	5	5	5	5	4	5	6	7	8	9	10	11
X	6	6	6	6	5	4	5	6	7	8	9	10
Y	7	7	7	7	6	5	4	5	6	7	8	9
e	8	8	8	8	7	6	5	5	6	7	8	9
d	9	9	9	9	8	7	6	6	6	7	8	9
c	10	10	10	10	9	8	7	7	7	7	8	9
i	11	11	11	11	10	9	8	8	8	8	8	9
j	12	12	12	12	11	10	9	9	9	9	9	9

Table 5.1 Matrix for Calculating Levenshtein Distance

Mean string length = 12
Levenshtein distance = 9
Normalised Levenshtein distance = 0.75

The matrix in table 5.1 above is generated by the recursive formula in equation 5.6. By reading values from the matrix, the distance between *any pair* of prefixes of the two strings can be established. For example, the distance between STU and LMN is three (outlined in grey on table 5.1) and the distance between STUVW and LMNOWXYe is seven (also outlined in grey). The Levenshtein distance for the two paths is the value in the bottom right hand corner of the matrix. In this case, the Levenshtein distance is nine. This means that it was necessary to perform nine operations (either substitutions or indels) on one string to transform it into the other string.

Once this information has been calculated, then the next task is to determine the *normalised* Levenshtein distance between the two strings. This essentially means dividing the Levenshtein distance by the average length of the two strings. Using the example above, the first string is 12 characters in length and the second string is also 12 characters in length. The mean length of the two strings is therefore also 12. The normalised Levenshtein distance is nine (the Levenshtein distance) divided by 12 (the average length of both strings) giving a value of 0.75. The reason for doing this is fairly straightforward. Imagine that there are two strings with a mean length of 13 characters, and the Levenshtein distance was only three. This would suggest that these strings were quite similar. However, if there were also a second pair of strings, this time with a mean length of only 4, and their Levenshtein distance was also 3, then common sense would dictate that these must be *less* similar than the first pair of strings. In this case, the Levenshtein distance becomes less significant for the shorter pair of strings. By normalising the value, we are taking into account the respective length of both of the strings, and hence making allowances for how significant the distance measure is. This method of normalising the distance is not a standardised procedure, instead it was developed for the purposes of this thesis.

The final stage of this whole technique is to calculate a *unique* value for each route, estimating how similar it is to *all* other routes in the sample, or indeed how dissimilar. This final step calculates the normalised Levenshtein distance between a single string and *every other* string in the sample, and then divides the sum total of those distances by (k-1) where k is the number of strings (or routes) in the sample. The number of subjects for 'World C' is 31, i.e. k = 31. Therefore, for each string in this example, thirty separate Levenshtein distance calculations were performed (the distance between a string and itself must always be zero). In total, for this sample of routes, 465 sets of calculations (similar to the matrix example above) were performed. Using this method a new value, the 'mean, normalised Levenshtein distance' can be calculated for every single route or string in the sample. This value represents how similar that string is to all the other strings, not just to a second individual string. The lower the value the more similar the string is to all other strings in the set, and the higher the value the more idiosyncratic it is.

From this point in the chapter, this value, the mean, normalised Levenshtein distance, will be referred to as the MNLD value. The final process of calculating an MNLD value for each string in the sample is rather difficult to perform by hand, purely due to the large combinatorial nature of the method. To analyse the data from the simulated environment experiment, a small programme in C language was written to automate this task.

Results

For the following series of figures in this chapter section, all the routes have been designated a colour based upon their MNLD value. The spectrum of colours allocated to the routes range from red at one extreme to blue at the other, passing through orange, yellow and green. The red routes represent a lower MNLD value (i.e. *fewer* changes, on average, are required to transform a route into any other route) and hence these are the routes which are *more* similar to all other routes. The closer to the blue end of the spectrum, the higher the MNLD value and the more idiosyncratic a route.

The colours are allocated proportionally using regular intervals between the maximum and minimum MNLD value for a sample, and then dividing this into regular intervals between the two. Each colour represents twenty percent of the range of values in a sample, i.e. red routes are the lower twenty percent. For this reason, some environments may have more routes coloured at the red/orange end of the spectrum, in these worlds a greater proportion of people took similar routes. In other worlds, there might be a more even distribution of colours. It would even be possible for a sample of people to have the same MNLD value (which could be high or low). A useful measure of a sample could be the distribution of MNLD values across a sample, characterising that sample. This overall measure could be used to indicate the homogeneity or cohesion of a group of routes.

The table opposite shows the seven test-environments listed alongside the spatial descriptor used for assigning the ASCII text identifiers.

It can therefore be seen that this method of representing and analysing routes can be used successfully with a variety of spatial descriptors.

Note that rooms and axial line segments were used for the Tate Gallery and for Barnsbury respectively. Since in the real Barnsbury and Tate these were the spatial units used for pedestrian observations, they were selected as being particularly appropriate to be used for ASCII assignment too.

Test Environment	Space for ASCII Assignment
World A - (Tate Gallery)	Rooms
World B - (Pilot Study 2)	Convex Spaces
World C - (Intelligible Urban)	Convex Spaces at Junctions
World D - (Unintelligible Urban)	Convex Spaces at Junctions
World E - (Triangular Grid)	Convex Spaces at Junctions
World F - (Square Grid)	Convex Spaces at Junctions
World G - (Barnsbury)	Axial Line Segments

Table 5.2 ASCII Assignment forall Worlds

Pilot World 1 (Tate Gallery), 'World A'

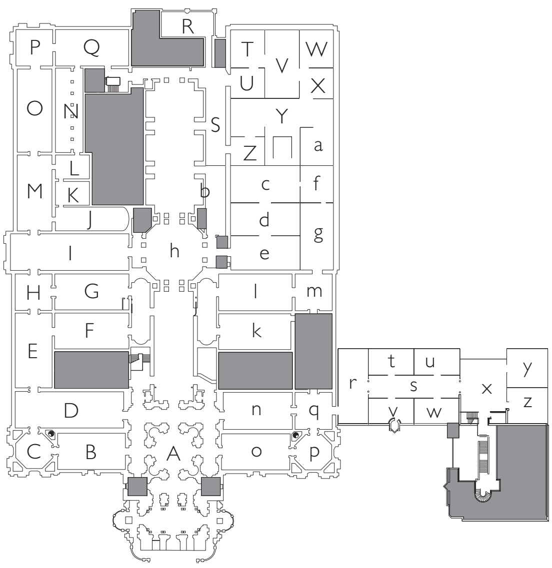


Figure 5.6 ASCII Space Allocation for World A

Subject	ASCII String	MNLD	No. of String	Colour
9	ABCDopqrsxzxsrqnA	0.836	17	Red
24	AopqrsxyxsrqnDCBA	0.839	17	Red
23	AnqpqrsxyxsrqnDA	0.842	16	Red
20	AopqrsxyxsrqnDEHIMOPQhA	0.852	23	Red
7	AopqrsvswsxyxsrqnA	0.863	18	Red
13	AopqrsxsrqnhRSUTVWXaYZShA	0.865	25	Red
18	AopqrsusxsrqnA	0.866	14	Red
15	ABCDEHGihSUTVXYZShA	0.874	19	Red
16	AhIMOPQPOMIHEDnqrsxsrqnA	0.897	24	Red
1	ABCDhSRUTVXYZheA	0.916	16	Red
2	AhIMOPQNLKJIHEFihnqprsvsxsrqnA	0.925	30	Orange
14	AnqrstsrqnhbhQNLKJMIHEDA	0.932	24	Orange
19	AhjlmgfcdehIMOPQhA	0.941	18	Orange
11	AhIMOPOMIHEDCBAopqrsvsxzxsrqpoA	0.953	31	Orange
12	ABCDEHIhedcdehIMOPQSUTVWXYZShA	0.953	30	Orange
10	AhbedehIMLKJKLNQRhABCBA	0.955	23	Orange
8	ADEHGihSRQPOMLKJMIHEDA	0.956	22	Orange
22	AhIhehQNLKJMIHGHEFihSUShABCBA	0.982	29	Orange
21	AnqpoABCDEFihA	0.995	14	Orange
6	ABCDEGHIMOPQhSUTVWXYZShehjkjhAopoA	1.007	34	Yellow
17	ABCDEHIMOPQPOMLMIhSUTVTUShedcfgmljkjhA	1.067	38	Yellow
3	AopqnDA	1.144	7	Green
5	AhedhA	1.194	6	Blue
4	AhjhA	1.251	5	Blue

Table 5.3 Route String Data for World A

For the Tate Gallery, being a building with many rooms, (in contrast to the other examples, which are urban environments or simulations of urban environments), these were held to be an appropriate spatial subdivision to use for ASCII assignment. The rooms and their individual ASCII characters can be seen on figure 5.6. For example, the first space that all subjects reach is space/room 'A', which is the entrance lobby. The Sackler Cupola is space/room 'h' and the Clore Gallery Extension comprises of rooms 'r', 's', 't', 'u', 'v', 'w', 'x', 'y' and 'z'.

In figure 5.7 opposite, note in particular, the blue routes that penetrate into the side galleries on the right hand side. One of these routes is yellow. It is yellow because although it passes through a relatively unpopular area, (the side galleries), this route also leads to the Clore Galleries, which were very popular, so the mixture of popular and unpopular produces a middle-of-the-range measure of popularity.

The most popular routes in this sample are the ones that lead into the Clore. This behaviour marks the major difference between subjects in the real Tate and in the virtual Tate (see the complete discussion of this phenomenon in Chapter 3. The main horizontal axis can be seen to be quite popular, but the cross axes are less popular, with the exception of the route into the Clore Gallery.

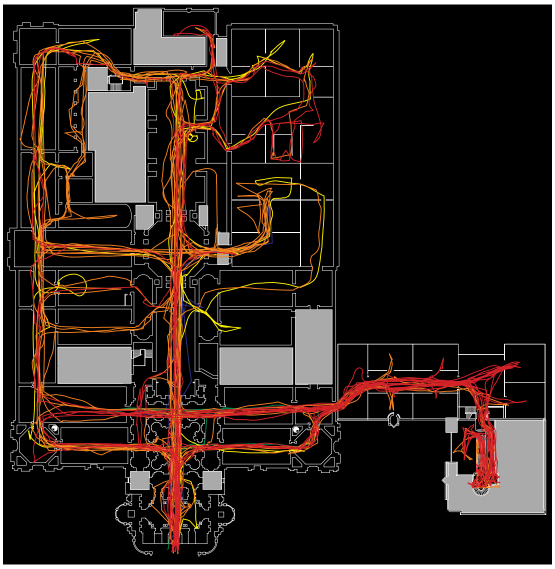


Figure 5.7 MNLD Strings in World A

Pilot World 2, 'World B'

Figure 5.8 opposite and table 5.4 below represent the routes that people took to the monument in the centre of this world, see Chapter 4 for more details on this world. There are four convex spaces in this world that lead to the central monument, these spaces are 'K', 'N', 'O' and 'R' and it should be noted that all routes have been cropped at the point of reaching any of these four spaces. In other words, only the routes taken to the monument were considered in this string-matching exercise, and any subsequent journeys taken after reaching the monument were ignored. That is to say, in this example it is the most popular route *to the monument* that is being calculated. There were 5 people who did not reach the monument, subjects, 2, 3, 9, 30 and 35 (14.29% of sample), and these subjects were not included in the string-matching calculation. World B used convex spaces for the ASCII assignment.

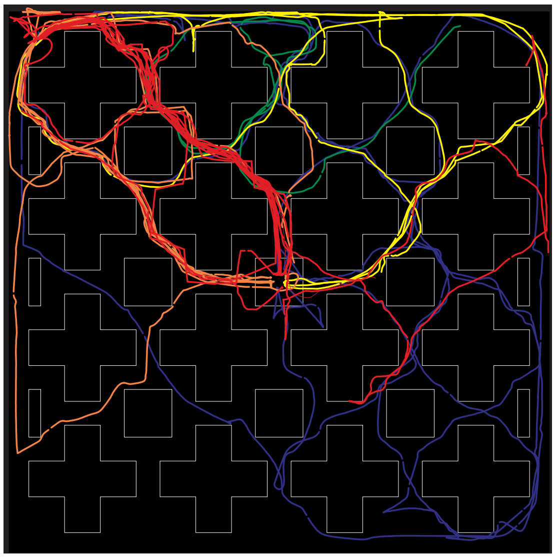


Figure 5.8 MNLD Strings in World B

The most common route choice, (those coloured red on figure 5.8), to the monument is the route that passes through the spaces ACGK, with an

Subject	ASCII String (To Monument)	MNLD	No. of Spaces	Colour
6	ACGK	0.56	4	Red
7	ACGK	0.56	4	Red
8	ACGK	0.56	4	Red
14	ACGK	0.56	4	Red
15	ACGK	0.56	4	Red
17	ACGK	0.56	4	Red
24	ACGK	0.56	4	Red
26	ACGK	0.56	4	Red
28	ACGK	0.56	4	Red
31	ACGK	0.56	4	Red
22	AFCGK	0.586	5	Red
32	ACGJN	0.627	5	Red
11	ACFJN	0.674	5	Red
5	AFJN	0.708	4	Orange
13	AFJN	0.708	4	Orange
20	AFJN	0.708	4	Orange
25	AFJN	0.708	4	Orange
29	AFJN	0.708	4	Orange
19	ADHK	0.733	4	Orange
10	ACGJFCGK	0.794	8	Orange
1	ACFTQN	0.798	6	Orange
23	ADHLO	0.821	5	Yellow
21	ABILO	0.839	5	Yellow
34	ABILO	0.839	5	Yellow
33	AFJGDEILO	0.912	9	Yellow
27	ACGDDGCDGK	0.939	10	Green
18	AMQUYbBEHK	1.08	10	Blue
12	AFJGDEILPSVYR	1.113	13	Blue
16	ADHLPWZbPLO	1.126	11	Blue
4	ADHLPSVZbWSO	1.167	12	Blue

Table 5.4 Route String Data for World B

MNLD value of 0.560. It is also possible to identify the second most popular route taken (coloured orange), which is an equally direct route, yet passes through an alternative set of spaces, these being AFJN, with an MNLD value of 0.708. In terms of actual distance (from the starting point to the monument in metres) and in terms of strategy (alternating *pairs* of left and right choices, 'RRLLRR' or 'LLRRLL'), these routes are identical. An examination of these two most popular routes begins to identify a certain *bias* to the sample. Those subjects who took the ACGK route, turned to their left initially (All subjects start in the corner of the world, facing towards the monument) to begin their wayfinding task. The subjects taking the AFJN began their journey by turning to their right. This left bias can also be picked up through the colour coding of the less popular routes too. The blue-est routes on the diagram, those identifying the most idiosyncratic routes of the sample, were those which passed through the bottom right hand sector of the plan.

Incidentally, in this particular example, the routes with the highest MNLD value also happen to be those that take the longest journey to the monument in terms of the number of spaces passed through. This appears to be a phenomenon peculiar to this world only and is discussed fully in the next section of this chapter, 'Correlation between MNLD value and Length of String', page 108.

Intelligible Urban World, 'World C'

Figure 5.9 opposite shows the entire routes, based upon both the journeys from the starting position to the monument in the middle and then the continuation of the subjects' journeys after reaching the monument. Figure 5.10 opposite is based upon a sub-sample of routes, considered only up until the point of reaching the monument. This calculation completely ignores any actions taken after reaching this destination point. In this way, this sub-sample examines the similarity of routes to the monument only. This dual approach to analysing the similarity of routes, up to and then after the monument (wayfinding goal) has also been applied to Unintelligible Urban World, 'World D'.

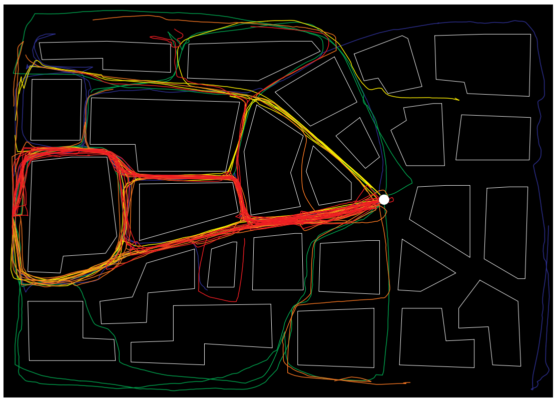


Figure 5.9 MNLD Strings in World C

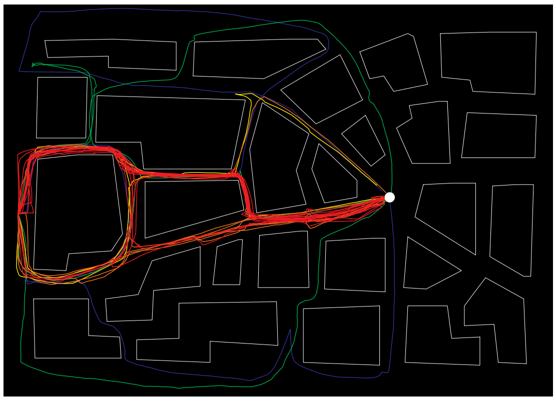


Figure 5.10 MNLD Strings in World C (to Monument only)

The predominance of the most popular routes is increased when considering only the routes taken to the cross. Clearly the majority of people took similar routes to the cross, and the greatest divergence took place when they attempted to find their way back to beginning. See tables 5.4 and 5.5 overleaf for the tabulated route data for World C.

Subject	ASCII String (Whole Route)	MNDL	No.of Spaces	Colour
12	LMNOWXYXWONML	0.509	13	Red
13	LMNOWXYXWONML	0.509	13	Red
16	LMNOWXYXWONML	0.509	13	Red
26	LMNOWXYXWOGFA	0.531	13	Red
15	LMNOWXYXWVUNML	0.534	14	Red
6	LMNOWXYXWOGB	0.541	12	Red
20	LMNOWXYXWVabW	0.559	13	Red
5	LMNUVWXYXWOGFE	0.569	14	Red
28	LMNUVWXYXWVUN	0.571	13	Red
18	LMNUVWXYXWVUNML	0.577	15	Red
3	STUNOWXYXWONUME	0.605	15	Orange
29	LMMNOWVWXYXWONML	0.606	16	Orange
30	LMNOWXYXdcj	0.611	11	Orange
17	STUNOWXYXHGFED	0.627	14	Orange
11	LMNOWXYHGBA	0.63	11	Orange
25	STUVWXYXWVUTS	0.636	13	Orange
31	STUVWXYXWVUT	0.637	12	Orange
19	LMNOWXYedcjk	0.638	12	Orange
10	STUVWXYXWVUTSLD	0.68	15	Orange
8	STUNOWXYXWVUTUVWO	0.702	17	Yellow
4	STUVWXYHGFED	0.709	12	Yellow
7	STUNOGHYHGONML	0.717	14	Yellow
27	STUNMLMNOWXYHGFED	0.719	17	Yellow
21	LMNOGHYHGFABIJ	0.743	14	Yellow
22	LMNOGBADEFGHY	0.786	13	Green
2	SijcdXYXdcjiS	0.816	13	Green
24	LMNUTSTZijkeY	0.836	13	Green
1	LMEFABIYIBAFE	0.842	13	Green
14	STUNMEDEMNOWXYI	0.865	15	Blue
23	LDEDDMNUTSLMNUVa	0.932	16	Blue
9	LMEFGBCKRhh	0.938	11	Blue

Table 5.5 Route String Data for World C

Subject	ASCII String (To Monument)	MNLD	No. of Spaces	Colour
12	LMNOWXY	0.343	7	Red
13	LMNOWXY	0.343	7	Red
16	LMNOWXY	0.343	7	Red
26	LMNOWXY	0.343	7	Red
15	LMNOWXY	0.343	7	Red
6	LMNOWXY	0.343	7	Red
20	LMNOWXY	0.343	7	Red
30	LMNOWXY	0.343	7	Red
11	LMNOWXY	0.343	7	Red
19	LMNOWXY	0.343	7	Red
5	LMNUVWXY	0.432	8	Red
28	LMNUVWXY	0.432	8	Red
18	LMNUVWXY	0.432	8	Red
3	STUNOWXY	0.445	8	Red
17	STUNOWXY	0.445	8	Red
8	STUNOWXY	0.445	8	Red
25	STUVWXY	0.514	7	Orange
31	STUVWXY	0.514	7	Orange
10	STUVWXY	0.514	7	Orange
4	STUVWXY	0.514	7	Orange
29	LMMNOWVWXY	0.522	10	Orange
21	LMNOGHY	0.537	7	Orange
27	STUNMLMNOWXY	0.589	12	Yellow
7	STUNOGHY	0.626	8	Yellow
14	STUNMEDEMNOWXY	0.742	14	Green
2	SijcdXY	0.743	7	Green
1	LMEFABIY	0.757	8	Green
24	LMNUTSTZijkeY	0.872	13	Blue
22	LMNOGBADEFGHY	0.874	13	Blue

Table 5.6 Route String Data for World C (to Monument only)

Unintelligible Urban World, 'World D'

In world D, there are fewer red routes but a larger proportion of the routes are yellow and green. In other worlds there is a greater variance amongst routes in World D than there are in World C. This may be because World D is far less intelligible than World C. However, if only the routes as far as the wayfinding goal are analysed, it is clear that a higher proportion of the routes are more similar. Once again the greatest divergence in subjects' routes appears to occur when they are instructed to make their way back to the starting position. In other words, this is the point at which many subjects appear to 'lose their bearing'.

Figure 5.11 MNLD Strings in World D

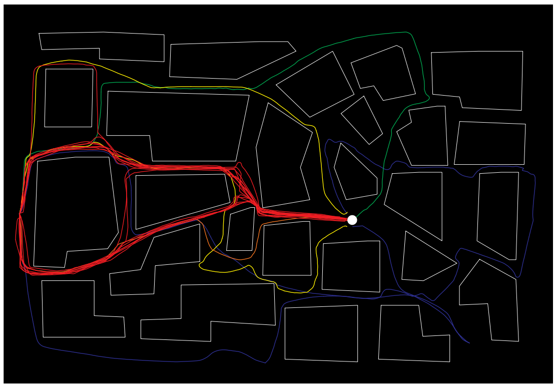


Figure 5.12 MNLD Strings in World D (to Monument only)

Subject	ASCII String (Whole Route)	MNLD	No. of Spaces	Colour
5	STUNOWoYoWVUTS	0.617	14	Red
4	STUVWoYoWVUTS	0.626	13	Red
6	STUVWoYoWVUTS	0.626	13	Red
7	STUVWoYoWVUTS	0.626	13	Red
8	STUVWoYoWVUTS	0.626	13	Red
25	STUVWoYoWVUTS	0.626	13	Red
26	STUVWoYoWVUTS	0.626	13	Red
12	LMNOWoYoWONML	0.655	13	Red
13	LMNOWoYoWONML	0.655	13	Red
15	LMNOWoYoWONML	0.655	13	Red
19	LMNOWoYoWONML	0.655	13	Red
27	LMNOWoYoWONML	0.655	13	Red
23	LMNOWoYoWVUTSij	0.672	15	Red
29	STUVaboYoWVUTS	0.676	14	Red
14	STUNOWoYoWOGB	0.681	13	Red
20	LMNOWoYobaVUTSi	0.701	15	Red
24	LDEMNOWoYHPQghl	0.808	15	Orange
30	STUVWONOGBA	0.862	11	Yellow
22	LMNOGFEDABlmPQ	0.877	14	Yellow
9	LMNOGHPQRQgflk	0.882	14	Yellow
2	LMNOWVabcdYdcbaZi	0.889	17	Yellow
3	STUVWOGFED	0.919	10	Yellow
28	LMNUTUVaabcdepfllk	0.927	18	Green
11	SijcdepflhRKCB	0.934	14	Green
17	SijcdepflfpYoWOG	0.95	16	Green
1	LDEFGHYHIBCJnQgY	0.955	16	Green
18	LMNUVabcdepfghRQPHY	0.957	19	Green
10	LMEFGBCJmPYPmIBA	0.962	16	Green
16	SSTUNOGBCK	0.981	10	Green
31	SijklfghRKC	1.000	11	Green
21	LMEFGBC	1.123	7	Blue

Table 5.7 Route String Data for World D

Subject	ASCII String (to Monument)	MNLD	No. of Spaces	Colour
12	LMNOWoY	0.443	7	Red
13	LMNOWoY	0.443	7	Red
15	LMNOWoY	0.443	7	Red
19	LMNOWoY	0.443	7	Red
27	LMNOWoY	0.443	7	Red
23	LMNOWoY	0.443	7	Red
20	LMNOWoY	0.443	7	Red
5	STUNOWoY	0.470	8	Red
14	STUNOWoY	0.470	8	Red
4	STUVWoY	0.491	7	Red
6	STUVWoY	0.491	7	Red
7	STUVWoY	0.491	7	Red
8	DEMNOWoY	0.564	9	Red
29	STUVaboY	0.615	8	Orange
2	LMNOWVabcdY	0.747	11	Yellow
1	LDEFGHY	0.801	7	Yellow
10	LMEFGBCJmPY	0.918	11	Green
17	SijcdepflfpY	1.017	12	Blue
18	LMNUVabcdepfghRQPHY	1.092	19	Blue

Table 5.8 Route String Data for World D (to Monument only)

Triangular Grid World, 'World E'

The assignment for Triangular Grid World was road junctions. In the example which applies string-matching methods to World E, the subjects' destination was the diagonally opposite corner (the bottom left corner on the figure). It can be seen from the distribution of colours that most similar routes never reached the wayfinding destination, i.e. reaching the goal was an uncommon act. This can be born out by examining the statistics, in fact only a small proportion of the subjects actually reached the opposite corner in this experiment. What is highly interesting is that it appears that more people took straighter routes to the wayfinding goal. It appears that the more idiosyncratic routes are also the most undulating routes.

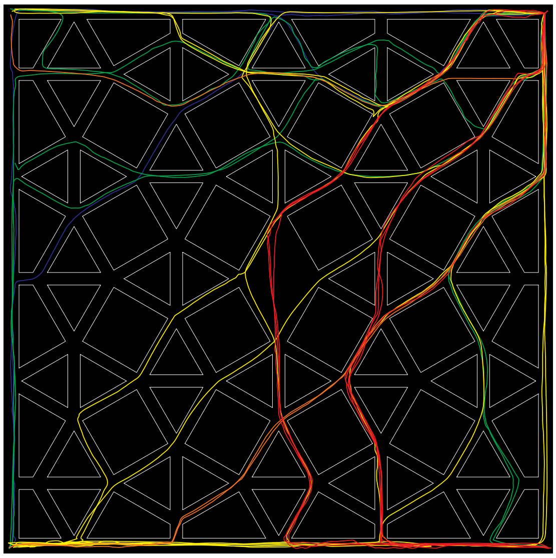


Figure 5.13 MNLD Strings in World E

Subject	ASCII String	MNLD	No. of Spaces	Colour
10	OZdimsz£$?	0.786	10	Red
2	GMSXhw5@$?	0.795	10	Red
11	GMSXhw5@$?	0.795	10	Red
31	GMSXhw5@$?	0.795	10	Red
9	ONTYcmsz£$?	0.815	11	Red
19	ONTYcmsz£$?	0.815	11	Red
21	ONTYcmsz£$?	0.815	11	Red
8	OZdimsw40&9	0.827	11	Orange
15	OZdimsw40&9	0.827	11	Orange
25	ONMSLKQJIH	0.837	10	Orange
6	OZdiox6£$@&9	0.85	12	Yellow
23	ONTYXRKDBA	0.85	10	Yellow
12	OZku8?$@&9	0.854	10	Yellow
22	OZku8?$@&9	0.854	10	Yellow
13	OZdimsz£$$@&9	0.857	13	Yellow
20	GMSXhlqv39	0.861	10	Yellow
24	GEDKRhw5@&9	0.866	11	Yellow
16	ONTYchry39	0.87	10	Yellow
7	GMSLKCBA	0.873	8	Yellow
29	GMSLKCBA	0.873	8	Yellow
14	ONTMSFLDKQJIA	0.887	13	Green
1	ONTYXRWVPU	0.893	10	Green
5	GMSLRWVaUep1	0.895	12	Green
3	GMFLKDBA	0.906	8	Green
27	GMSLKCJIHUep1	0.908	13	Green
18	OZdiox7?	0.91	8	Green
30	OZdiox7?	0.91	8	Green
26	GEDBAHUep1	0.928	10	Blue
17	GMSLDBA	0.938	7	Blue
28	GEDKQVafep1	0.941	11	Blue

Table 5.9 Route String Data for World E

Square Grid World, 'World F'

The assignment for Square Grid World was based upon junctions. The routes through this world that are most popular are those that pick out the most direct diagonal route from corner to corner.

A smattering of blue routes can be identified in the top left-most corner of the world and yellow and green routes are to be seen in the opposite corner.

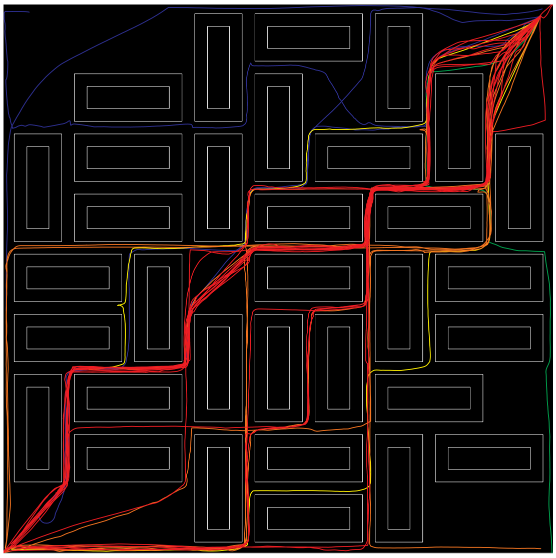


Figure 5.14 MNLD Strings in World F

Subject	ASCII String	MNLD	No. of Spaces	Colour
2	FEKQPWVjihnt	0.497	12	Red
5	FEKQPWVjihnt	0.497	12	Red
14	FRQPWVjihnt	0.497	11	Red
16	FRQPWVjihnt	0.497	11	Red
25	FRQPWVjihnt	0.497	11	Red
26	FRQPWVjihnt	0.497	11	Red
28	FEKQPWVjihnt	0.497	12	Red
31	FEKQPWVjihnt	0.497	12	Red
7	FRQPONVjihnt	0.556	12	Red
10	FEKQPONVjihnt	0.564	13	Red
23	FEKQPWdcVpuxt	0.582	13	Red
13	FRQPWdcqpuxt	0.583	12	Red
27	FRQPWdcqpuxt	0.583	12	Red
19	FRQPWdcqpont	0.586	12	Red
21	FRQPWVjot	0.59	9	Red
11	FEKQPWdkrvyxt	0.606	13	Red
20	FEKQPWdkrvyxt	0.606	13	Red
8	FRQPONVpuxt	0.619	11	Orange
24	FRQPWVUTSagt	0.622	12	Orange
4	FEKQPWVji	0.649	9	Orange
6	FRQPWdkrvyw	0.668	11	Orange
29	FRYXWdcqpuxt	0.671	12	Orange
18	FRRYXWVpuxt	0.677	11	Orange
15	FRYXWdkrqpot	0.709	12	Orange
22	FRYXWVUTSagt	0.71	12	Orange
30	FRYXelkrvuxt	0.745	12	Yellow
3	FEKHONVUbi	0.821	10	Yellow
9	FEKQRYZfmw	0.861	10	Green
1	FEKHGJIA	0.96	8	Blue
17	FEDCBASa	0.991	8	Blue
12	FEKHONVjihntnhibUVNOHDEF	1.048	24	Blue

Table 5.10 Route String Data for World F

Subject	ASCII String	MNLD	No. of Spaces	Colour
3	.,?!![]£{}¡~^51rqy	0.795	18	Red
18	.,?!![]£$¡~^51nlo287&	0.801	21	Red
15	.,?!![]£{}¡~^51soljYjhgxfev	0.831	27	Red
8	.,?!v![@34^~¡$¡~^56&	0.835	20	Red
28	.,?!vew@]£$¡¶~^51s28*7&	0.841	23	Red
26	.,?/[]£$¡~^51somaYihgfevew	0.85	26	Orange
19	.,?[]£]@3456&61rzqy3@§]	0.852	23	Orange
27	.,?!![]£$}{][/!![]{}¡™#¢¢+	0.869	26	Orange
11	.,?[§@34^~¶¡{}£$¡™#+)&7	0.877	23	Orange
9	.,?[]£$¡~^4ypghihgfedcQHAB	0.893	26	Orange
5	.,?!vew34^~™#+)+#™~^4ypghgf	0.896	27	Orange
7	«÷/!![]{}¡~^51rqy3@	0.896	19	Orange
13	.,?!vefghgpy4^~™#++#™~^4ypfe	0.909	28	Yellow
4	.,?!![]£$¡™#+	0.913	13	Yellow
20	.,?0tQHABIOUedew34	0.93	18	Yellow
10	.,0tQHHQcdew3@§:;'"Æ...°¢+	0.937	24	Yellow
23	.,?[@3456&&61rqpggpqr1543wfpq	0.941	29	Yellow
29	.,?!![@3yqrnjhgfw@[!![§:|;'¶¡™#+	0.945	32	Yellow
31	.,0tQHHQcdew3451nk	0.95	18	Yellow
24	«÷/[@3451nkaaYihgfevew34	0.969	24	Green
16	.,0tQHABCDEFGGFEDC	0.989	18	Green
1	.,.«¿:;'"Æ...>°¢+)&7	0.99	18	Green
6	.,?!![@3yqr	1.009	11	Blue
25	.,?[§]∞£]@3yqrs2876551njYZabWVKCDKP	1.011	35	Blue
17	«÷/!![@wfpqzqy	1.051	14	Blue
22	.,?[@wfghijhgfUJBAHQt0?!vefpqrnkZVKDE	1.062	37	Blue

Table 5.11 Route String Data for World G

Barnsbury, 'World G'

The pattern of most popular routes for the simulation of Barnsbury is reminiscent of the various patterns of integration shown at the end of Chapter 4. Certain main roads emerge as particularly red (well-frequented) in contrast to a number of side streets, down which very few subjects made their way.

Figure 5.15 MNLD Strings in World G

Correlation between MNLD value and Length of String

It has been suggested that there might be a correlation between the length of a string and its MNLD value. Although this seemed unlikely, since the string-matching algorithm is normalised to taken the length of both the strings into account, it was decided to investigate whether there was a correlation between string length and MNLD value. Regression analysis was performed between the number of characters forming a string and that string's mean similarity measure. This was performed for all strings in all worlds. The results are presented in table 5.11. Although there is a strong correlation between length of string and MNLD value for the routes through World B[8], this is the exception

World	R-squared value
A	0.094
B	0.814
C	0.014
D	0.0004575
E	0.047
F	0.025
G	0.003

Table 5.12 Correlation Coefficients of String Lengths and MNLD Values for Worlds A-G

rather than the rule (in this world all the more similar strings were short and the longer strings more dissimilar). The r-squared values for the rest of the worlds are close to zero. It may be stated that there is no correlation between string length and MNLD measures.

Conclusions

The analysis of the virtual environment experiment data and subsequent visual representation of the MNLD values of the routes, strongly indicates that as a tool, the string-matching technique can be usefully applied to an area of research such as spatial decision analysis or wayfinding. This chapter documented a tentative exploration into such an application and subsequent adaptation of string-matching techniques. The initial results have proved encouraging and it is hoped that this is a method of analysis that can be further developed[9] for architectural applications.

Through analysing the paths taken by all the subjects through all the worlds, it can be noted that the most popular routes through an environment are those that pass along the more syntactically integrated roads. This finding confirms observations made 'by eye' at the end of the previous chapter, Chapter 4. It can also be noted that the routes that emerge as being the most popular (most red) are predominantly those that are the 'straightest' routes through an environment. It is further suggested, that this observation might indicate the types of small-scale actions which could be relevant to the problem being investigated by this thesis. In looking for the relationship between small-scale actions and resultant emergent patterns, it can be asked, "What kinds of actions could result in routes that are chiefly linear?" Methods to investigate this phenomenon and to identify which actions could be causing it to arise are explored in the following chapter, Chapter 6.

Key Points

- It is possible to compare routes by means of a cumulative measure of spaces through which the subject has passed.
- There is no correlation between MNLD and the length of the string (spaces passed through).
- Many of the most popular routes appear to be very 'linear' and many of the least popular routes appear to be very undulating. It is concluded that it would be useful to be able to measure the linearity of routes.

Notes

1 Levenshtein distance is defined by Graham A. Stephen in Stephen, G. A. (1992). String Search. Bangor, University College of North Wales. as being "a distance metric between two strings, not necessarily of the same length, given by the minimum number of symbol insertions, deletions and substitutions required to transform one string to the other, e.g. the Levenshtein distance between zeitgeist and preterit is 6."

2 ASCII abbreviation for American Standard Code for Information Interchange.

3 'Metric distance' is the correct term used in string-matching. It has no relationship to actual distance measured in metres (or any other unit measure of length).

4 This is a string matching algorithm based on string distance and the longest common subsequence as defined in Wagner, R. A. and M. J. Fischer (1974). "The string-to-string correction problem." Journal of the ACM **21**(1): 168-73.. In his technical paper Stephen, G. A. (1992). String Search. Bangor, University College of North Wales., Graham A. Stephen defines a subsequence as being "of a string x - a string obtained by deleting zero or more symbols, which need not be contiguous, from x, e.g. nnnaa is a subsequence of ginnungagap. A *proper* subsequence of x is a non-empty subsequence not equal to x itself.

5 For the purposes of this chapter, 'large' is defined as ten or more.

6 The Hamming distance is defined by Graham A. Stephen in Stephen, G. A. (1992). String Search. Bangor, University College of North Wales. as being "a distance metric between two strings of equal length, equal to the number of symbol positions at which the two strings differ, e.g. the Hamming distance between master and pastes is 2".

7 This is defined as any sub-string of the whole string on the condition that they both start from the same space (or ASCII character).

8 This purely means that in World B, more people took shorter routes (i.e. found their way efficiently) and a few people took extremely long routes (i.e. became very lost).

9 Some further applications of these string matching methods are included at the end of this thesis in Appendix A.

Chapter Six:
Route Choice Decisions, Conservation of Linearity and Isovists along Routes

Abstract

This chapter examines the actual decisions made by subjects at junctions in urban systems using the virtual world, 'World E' as a test environment. Each route is broken down into its constituent junctions (where route choice decisions were made). At each junction the decision made (in terms of the angle described between the junction approach road and the road selected) is noted. Maximum, mean, minimum and randomly chosen[1] angles are also calculated for each junction. It is then demonstrated that a route can be expressed both as a sum of the individual decisions made and as the sum of all possible decisions available during a journey (i.e. potential choices). These values are then calculated for each of the thirty routes through this test world. The relationship between these values are then analysed statistically, showing that the decisions made at junctions correlate more strongly with the maximum angles of incidence at a junction, compared to any other measure. Finally, this chapter concludes by presenting a method of visualising the changing properties of isovists along a route. The resultant graph produced is termed the 'Route Vision Profile' and examples of these graphs are shown.

Introduction

So far, this thesis has yielded a primary research question, which is to investigate the small-scale actions that produce cumulative patterns of movement identifiable in buildings and urban areas. It has also proposed a secondary question "Can we use studies of people's behaviour in virtual environments to learn about their likely behaviour in the real world?" To this end, a number of wayfinding experiments were conducted in seven virtual worlds and the subjects' movement data recorded. After initially visualising their paths, it was noted that people were moving through the virtual worlds in a manner that appeared to reflect configurational analyses of the spatial layout of the environments. To substantiate this observation, patterns in the path-data were sought. A method for establishing the most popular path from a sample of routes was developed which led to the conclusion that the most common paths in these worlds also appeared to be the 'straightest'. The first half of this chapter will attempt to verify this hypothesis.

The majority of this chapter is also methodological, as it presents a novel method for analysing the 'straightness' of a route. Once again, this is a 'top-down' approach in that it considers characteristics of the route or path *as a whole*, before considering what local rules might give rise to such patterns. Although primarily a methodological chapter, after applying this technique to all the route-data from one of the experiments, it is hoped that the outcome may contribute to answering the question of what kind of small-scale actions are important in understanding pedestrian movement. At the end of this section, another purely methodological section is introduced, which examines the changing field of view along a route. Although no substantive conclusions are drawn from this method of analysis, it serves to introduce the concept that what we see, or what information is visually available to us as we move through an environment may be critical to determining our actions (as suggested at the end of Chapter 4). After considering the visual field available along a route, the thesis will shift its focus; instead of considering movement from a 'top-down' perspective it will use a 'bottom-up' approach. This is developed in the following chapter, Chapter 6.

In the previous chapter, Chapter 5, it was demonstrated that the most popular routes in a sample of routes (as calculated using string matching techniques) also appeared to be more 'linear' than would be expected were random route-choice decisions being made. The question that this observation prompts is *what* route choices are individual subjects making at road junctions such that these actions result in an apparent conservation of route linearity? In this chapter, therefore, a method is proposed for the determination of route choice decisions, as made at consecutive road junctions over the duration of an entire journey. This method uses a measure of angular deviation (from a straight line or straight direction) and develops a cumulative measure for an individual's whole journey, based upon the summation of all choices made at every junction encountered along the route.

The hypothesis that this method was developed to test, is that an individual subject will follow as straight a line as possible with minimal angular deviation (from a straight line), on condition that this choice is always approximately in the direction of their goal. It could be argued that another way of stating this hypothesis in lay terms is that essentially people 'follow their noses'.

The Test World

Of the sample of seven virtual worlds used as test environments for this thesis, one was held to be more suitable than the other worlds for the purpose of testing a measure of angular deviation. This suitability was assessed using two criteria (described in full opposite). The world used to test this hypothesis and hence this method, is 'World E' or 'Triangular Grid World' (see Chapter 4, for a fuller description of the seven worlds). This particular world is a simulation of an urban environment, with a variety of building footprint shapes (the majority of blocks are either squares or equilateral triangles). See figure 6.1 below for an eye-level view of this world.

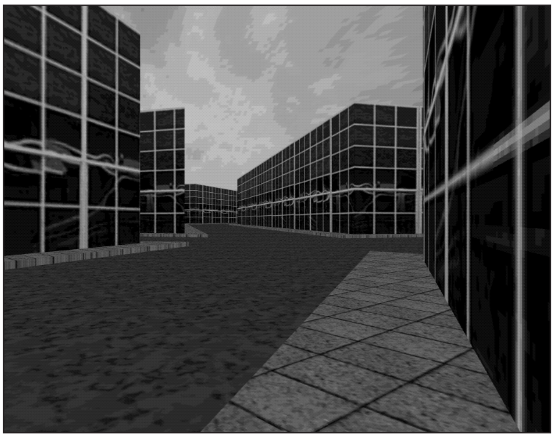


Figure 6.1 Screenshot of World E

The subjects participating in this experiment were in the virtual world for a maximum of ten minutes and their walking speed approximated a real world walking speed. All the subjects entered the virtual environment and started 'walking' from the same starting position (the top right-hand corner in plan) and were instructed to 'walk' to the opposite corner, by the most direct and hence most efficient route possible. The subjects were requested not to walk around the outer edges of the world and the majority of the subjects heeded this instruction.

There were two design criteria for this world, which were also the same criteria, which caused it to be the most suitable environment for testing a measure of angular deviation. The first criterion dictated a standard length of 'street' to be used wherever possible. The use of a standard street length ensured that the subjects could not be basing their route choice decisions upon this factor, e.g. choosing to follow the longest street at each junction. The second criterion for the design of this test environment concerned the *type* of junctions formed by the streets. It was determined that the street system in the world should consist of as large a variety of junction types as possible. A subject is therefore presented with a range of different choice decisions. The variety of junctions constituting this urban simulation varied both in terms of the actual number of route choices available at any single junction (e.g. at a crossroads the number of route choices is four) and by the angles described between the streets leading from a junction. In some situations the choice available would consist of various symmetrically equal options and in other situations of asymmetrically placed options with reference to the route and direction taken leading to that junction.

To illustrate briefly this idea of junction symmetry, imagine a fork in a road (such as the leftmost diagram of figure 6.2 overleaf). It is being approached from the single street that suddenly forks into two (in the direction of the arrow on the diagram). This could be described as a symmetrical route choice scenario, in that both choices appear identical (from an angular definition) when approached *from that particular direction only*. This condition can be expressed mathematically. If all lines of symmetry of a junction are first identified and then if any of these lines of symmetry are coincident with the centre line of any of the roads forming that junction, then when approaching the junction from that road or roads, the choice presented will be a symmetrical one.

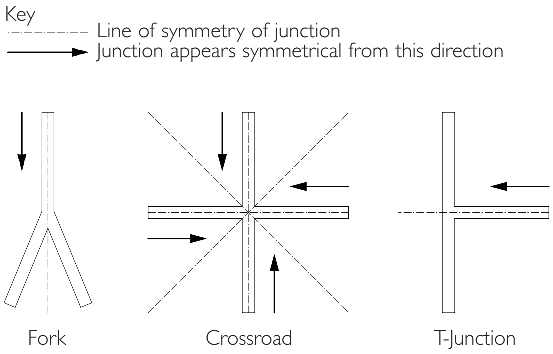


Figure 6.2 Symmetry of Junction Types

Returning to the case of the fork, only one road and hence only one direction will give rise to a 'symmetrical choice'. In this case there is only one line of symmetry which is coincident with a road centre line and therefore the junction will appear symmetrical if and only if approached from the direction of the arrow marked on the diagram. When approaching the same junction from one of the other two streets the choice no longer appears symmetrical.

If we consider a classic crossroad junction, there are four lines of symmetry, but two of them are not coincident with any road centre lines (see the centre diagram of figure 6.2). Of the other two lines of symmetry, we find that each is coincident with two of the four roads forming this junction. Therefore a classic crossroad will appear symmetrical from whatever direction approached. Finally the rightmost diagram of figure 6.2 shows a classic T-Junction. It can be clearly seen that this has only one line of symmetry and that the line is coincident with the centre line of only one road. In this case it is only when approaching the junction from the direction of the arrow, that the choices presented will appear to be symmetrical.

In 'World E' or 'Triangular Grid World' the numbers of choices at junctions ranged from three (a classic T-Junction) to ten (where a number of streets converge in the centre of the world). This world also contained a large range of junction types affording both symmetrical and asymmetrical route choices. The minimum angle between any two roads in this world is 60° and the maximum angles 180° (straight on) and 150°.

This experiment was conducted in a manner identical to all the other experiments, see Chapter 4, by subjects navigating immersively through the virtual world. The male subjects constituted 68% and the female subjects 32% of the total subjects. There were thirty volunteers participating in this experiment with a mean age of 28.

Method of Analysis

Before the route of each subject can be analysed individually, each junction in the world needs to be identified and tagged. Every junction, that is to say every location where a route choice decision has to be made, is marked with a unique identifier, in this case an ASCII text marker. These junctions will be referred to in this chapter as route choice nodes. In 'World E' sixty-seven such route choice nodes were identified and named. The junctions are circled on figure 6.3 overleaf along with their ASCII text markers.

The route of each individual subject can then be broken down into a sequence of chronologically ordered route choice nodes. To illustrate this process a single route can be analysed as follows. Figure 6.4 shows the initial portion of a single route taken by an individual subject (number 021).

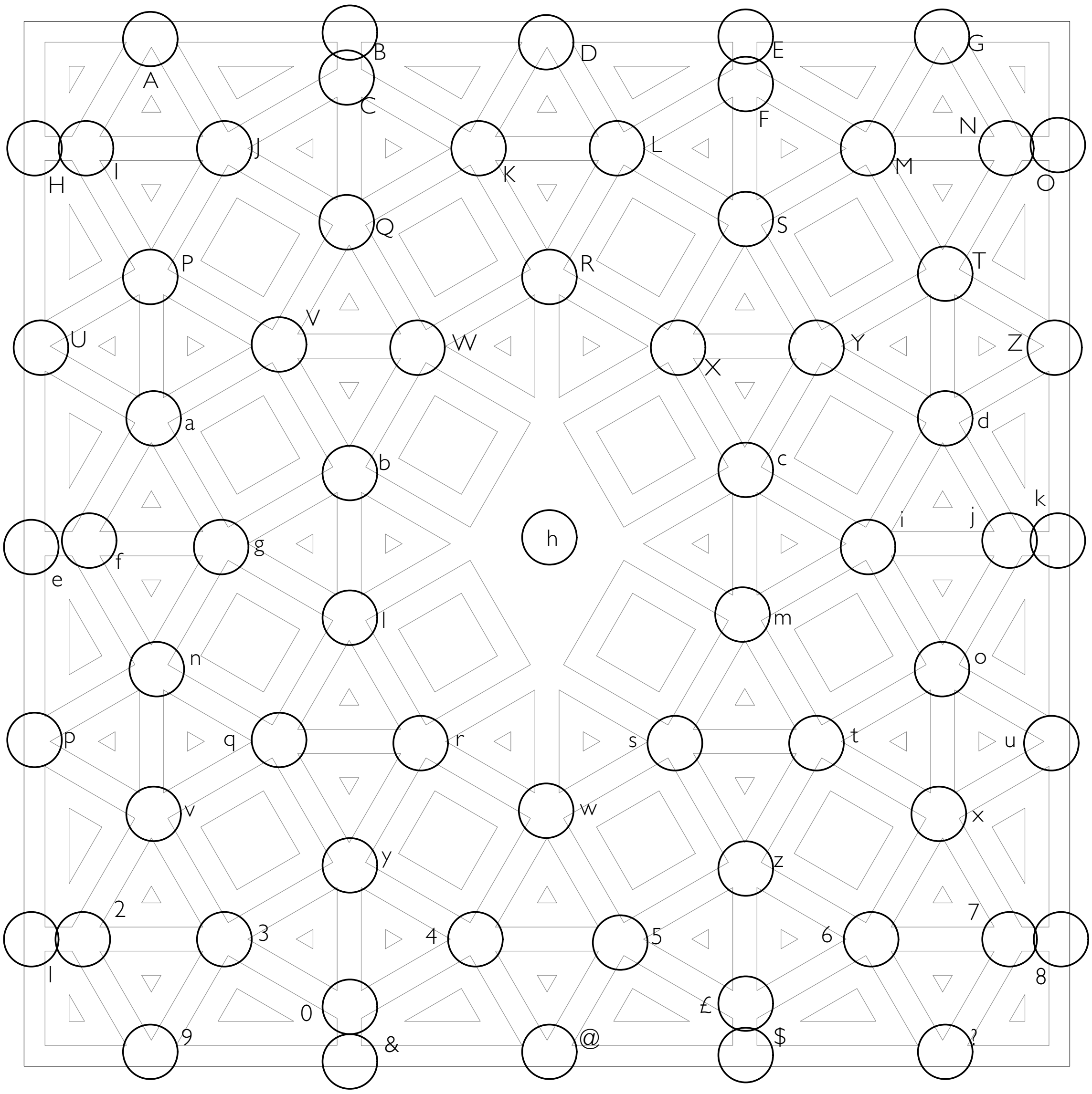


Figure 6.3 Identification of Road Junctions

It can be seen on figure 6.4 overleaf that the subject passed through the route choice nodes labelled ‘O’, ‘N’, ‘T’, ‘Y’, ‘c’ and finally ‘m’ (after node ‘m’ the route taken is no longer shown in figure 6.4). These nodes can be listed sequentially in the order in which the subject encountered them. By listing the nodes in this manner, it can easily be seen that the first location where the subject needed to make a decision was route node ‘O’ and that the second location was route node ‘N’ and so on. By continuing to list the route choice nodes in this way, the entire journey can ultimately be represented as a string of ASCII text characters. The following ASCII text string can be used to represent this particular subject’s journey

O-N-T-Y-c-m-s-z-£-$-?

At node ‘O’, the subject had a choice of two possible options. They could have taken the first right turn (i.e. turned through an absolute angle of 90°) or continued in a straight line, which can be considered either as 0° or 180°. For the purposes of this

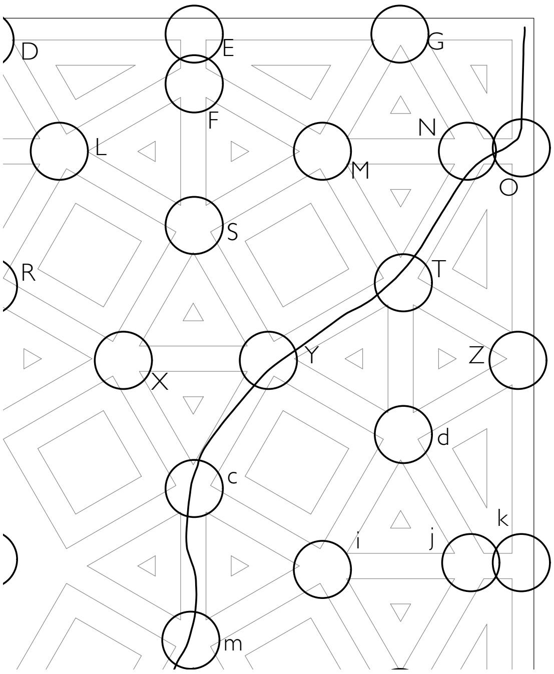


Figure 6.4 Portion of a Journey through World E

chapter, continuing straight on will be held to be 180°. When first developing this method of choice analysis, the option of turning around completely and heading back in the direction from which the subject had already walked, was also counted as a valid choice. This option was held to be equivalent to an angular choice of 0° (which is historically why the choice of 'straight on' was considered to be 180° rather than 0°[2]). Therefore the number of choices available at each junction originally included the option choosing the road along which the subject had just travelled. For example, at choice node '0' instead of two choices there would be three, since returning to the starting point would also be considered to be a valid option. However after analysing all decisions made by all subjects at all junctions, it was apparent that none of the subjects in the sample ever made such a choice (termed 'backtracking' in wayfinding literature) and it was ultimately removed from the analysis. Subsequently the number of choices available was calculated as being the number of roads forming the junction, less the approach road (i.e. n-1). However the convention of counting a 'straight on' choice as 180° rather than 0° remained unchanged. This is the convention used in the rest of this chapter and thesis.

Therefore for node 'O', we can state that the absolute angle (it is irrelevant whether it is to the left or to the right, i.e. all angles are positive) that the subject turned through at node 'O' was 90°. The number of choices available were two (turning back was not counted as an option), the maximum angle the subject *could have* chosen was 180° (i.e. gone straight on) and the minimum angle they could have chosen was 90° (turned right). The average value of the available choice angles at node 'O' was 135° or (90° + 180°)/2. All of these values are shown in the first six columns of the first row of table 6.1 overleaf and represented graphically in figure 6.5 below.

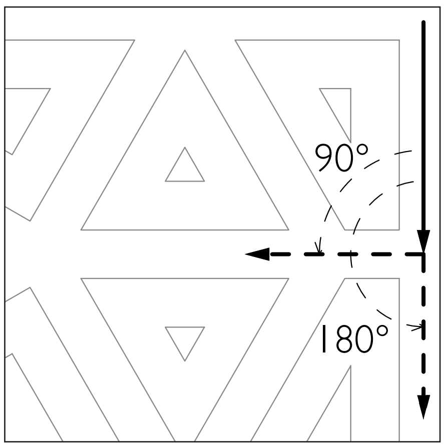


Figure 6.5 Available Route Choices at Node "O"

Also included in table 6.1 is a random choice of route decision (columns seven and eight). This choice was produced by using a random generator (column seven), based on the number of options available (column four). Essentially in the case of

Route 021 Spaces	Abs. Angle Turned Through	Mean Angles at Route Node	No. of Route Choices	Max. Angle of Incidence	Min. Angle of Incidence	Random Choice of Angle	Angle Chosen Randomly
O	90	135	2	180	90	0	90
N	120	140	3	180	120	0	120
T	150	112.5	4	150	60	0	60
Y	150	112.5	4	150	60	1	150
c	150	112.5	4	150	60	1	150
m	150	105	4	150	60	1	150
s	120	105	4	150	60	0	90
z	150	112.5	4	150	60	0	90
£	180	100	3	180	60	1	180
$	90	90	2	90	90	1	90
?	180	120	3	180	60	2	180
ONTYcmsz£$?	139.09	113.18	3.36	155.45	70.91	0.64	122.73

Table 6.1 Example of Examining Angles Turned Through for a Single Route

node ‘O’, this would represent a person flipping a coin (since there are only two valid choices at this junction) to determine which route to take. The route is then selected by counting the streets, as they appear in the world, moving in an anticlockwise direction from the approach road. For example, at node ‘O’, as the subject rotates in an anticlockwise direction (starting from the approach road) the first street is counted as choice 0, the second street choice 1 etc. Since the random generator produced a choice of zero at this junction, then the first choice counted in an anticlockwise direction is 90° (column eight). This process is analogous to the subject stopping at a junction, flipping a coin or throwing a dice (or performing an equivalent random act) in order to make a route choice decision. The subject then notes down what the outcome of the random process *would have been*, but nevertheless decides to make his or her own decision regardless of the outcome of the random act. The randomly generated choice does not, therefore, constitute a randomly generated *route* through the virtual world, it only represents a single random choice made at each individual node or junction and furthermore a choice that is *not acted upon*.

Returning to the route of subject 021, the next choice node this subject reached was node ‘N’. The choices at this junction were quite different to node ‘O’. This time the subject has a choice of three routes to take. Listed in an anticlockwise direction, they are 120°, 180° and 120° again. The second 120° option is listed as 120° rather than 240° because we are primarily interested in the deviation from the straightest route and not interested in the ‘handedness’ of the choice selected. Another point to note about this node is that here the choices appear to be symmetrical when approaching the junction from the direction of node ‘O’, see figure 6.4 overleaf.

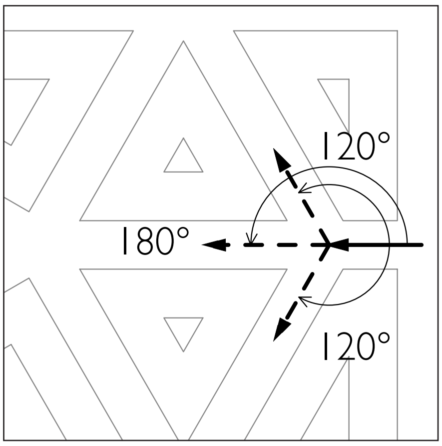


Figure 6.6 Available Route Choices at Node “N”

At node ‘N’ the subject chose to take the leftmost road (considered from the direction of ‘O’), choosing one of the 120° options. The maximum angle they could have chosen was 180°, the minimum choice being 120°. The mean choice would have been 140° (120°+180°+120°)/2. This time the random generator also selected choice zero (namely the first street to appear when turning in an anticlockwise direction, starting from the current street). In this case choice 0°, the random choice, would also have been 120°. This data can be read off row two of table 6.1.

If this process (of analysing all possible choices and recording which choice the subject makes) is repeated for every junction encountered by this subject during the journey O-N-T-Y-c-m-s-z-£-$-?, then this information can be entered into each row of the table 6.1 (overleaf) until the choice data for each junction is completed.

To summarise, this subject passed eleven locations where route choice decisions needed to be made. The average choice of angle can now be determined for the route as a whole. This is measured by taking the absolute angle selected by the subject at each individual node and calculating the average value of all angles selected at all nodes constituting the route. On average, therefore, this subject chose an average angle of 139.09° over the entire route. This is the figure shown in the final row of column 2 of the table. The average maximum angle available for choice over all eleven junctions can also be calculated and is shown in the last row of column 5 of table 6.2. For subject number 021 the mean maximum angle value is 155.45. The final value in column 6 shows the average minimum angle over the eleven junctions, which is 70.91. The column entitled 'Mean Angles at Route Node', which is the third column, calculates the average angle of all choices at any individual node and then calculates the average angle over the journey as a whole. For subject number 021 this value was 113.18. Finally the fourth column shows the average number of choices available throughout the journey, which, in this example is 3.36 and the final column shows the value of the randomly chosen angle, at each junction, averaged over the duration of the subject's journey.

Once the choices made by each subject at each junction along their journey have be translated into average values for the journey as a whole, it is possible to compare these average-route values to every other subject participating in this experiment.

Results

In table 6.2 overleaf, are shown the route choice data averaged over the duration of the whole journey for each subject participating in the experiment. Each route was broken down into the choices available and the decisions actually made at each junction, in exactly the same manner illustrated in the previous example for subject number 021. Column 1 of table 6.2 shows the subject number, column 2 shows the ASCII string representation of the route, listing the junctions the subject encountered and the order in which they passed through them. The third column shows the average choice of angle that each subject made over the duration of the journey. For example, if a person, hypothetically, were always to take a right turn followed by a left turn whilst navigating (an option not actually possible in 'World E') then the average angle chosen by that person throughout their journey would be 90°, since this would be their choice at every junction. Equally using a second hypothetical example, if a person were to choose to go straight on at every junction

Subject No.	Route Represented as an ASCII String	Mean Angle Turned at Nodes	Mean of all Angles Selected at Nodes	Mean No. of Choices Available	Mean Maximum Angle of Incidence	Mean Minimum Angle of Incidence	Mean Random Choice of Angle	Mean Angle Chosen Randomly
001	ONTYXRWVPU	133.33	114.72	3.67	156.67	70.00	1.33	123.33
002	GMSXhw5@$?	138.00	108.00	4.00	159.00	57.00	2.00	111.00
003	GMFLKDBA	120.00	109.69	3.25	153.75	63.75	1.38	123.75
005	GMSLRWVaUep1	137.50	112.29	3.42	157.50	65.00	1.08	130.00
006	OZdiox6£$@&9	147.50	112.71	3.17	155.00	67.50	1.25	117.50
007	GMSLKCBA	135.00	107.19	3.38	146.25	63.75	1.00	116.25
008	OZdimsw40&9	144.55	108.64	3.36	150.00	65.45	1.27	100.91
009	ONTYcmsz£$?	139.09	113.18	3.36	155.45	70.91	1.09	103.64
010	OZdimsz£$?	147.00	109.75	3.30	156.00	66.00	1.10	123.00
011	GMSXhw5@$?	138.00	108.00	4.00	159.00	57.00	1.30	87.00
012	OZku8?$@&9	180.00	127.50	2.50	180.00	75.00	0.80	132.00
013	OZdimsz£$$@&9	154.62	114.42	3.08	161.54	69.23	0.92	101.54
014	ONTMSFLDKQJIA	90.00	107.12	3.46	154.62	66.92	1.38	117.69
015	OZdimsw40&9	144.55	108.64	3.36	150.00	65.45	1.55	114.55
016	ONTYchry39	141.00	113.00	4.10	156.00	63.00	1.70	111.00
017	GMSLDBA	145.71	111.07	3.29	158.57	64.29	1.57	132.86
018	OZdiox7?	131.25	107.81	3.38	150.00	63.75	1.50	112.50
019	ONTYcmsz£$?	139.09	113.18	3.36	155.45	70.91	1.45	117.27
020	GMSXhlqv39	138.00	103.50	4.30	153.00	54.00	2.20	105.00
021	ONTYcmsz£$?	139.09	113.18	3.36	155.45	70.91	0.64	122.73
022	OZku8?$@&9	180.00	127.50	2.50	180.00	75.00	0.80	129.00
023	ONTYXRKDBA	135.00	115.00	3.30	159.00	72.00	1.10	126.00
024	GEDKRhw5@&9	152.73	112.50	3.73	163.64	65.45	1.45	109.09
025	ONMSLKQJIH	138.00	111.00	3.40	153.00	72.00	1.10	123.00
026	GEDBAHUep1	180.00	127.50	2.50	180.00	75.00	0.50	117.00
027	GMSLKCJIHUep1	150.00	112.31	3.15	156.92	66.92	1.08	115.38
028	GEDKQVafep1	150.00	112.73	3.09	155.45	68.18	0.64	111.82
029	GMSLKCBA	135.00	107.19	3.38	146.25	63.75	1.00	116.25
030	OZdiox7?	131.25	107.81	3.38	150.00	63.75	1.00	116.25
031	GMSXhw5@$?	138.00	108.00	4.00	159.00	57.00	1.70	102.00

Table 6.2 Analysis of Angular Choices made by all Subjects in World E

(assuming a world where this were possible) then the average angle over their entire route would be 180° (using the angular conventions established earlier in this chapter). Column 4 in the table shows the average choice of angles available to the subject over their chosen route. This is simply a measure of the average angle of all available choices at any single junction, which is then averaged over the journey as a whole. This measure is most usefully read alongside columns 6 and 7, which show the average, maximum angle and average minimum angle available over the route. This is simply a case of noting down the maximum angle of incidence available at every junction and then averaging it over the whole journey and then performing the same calculation for the minimum angle of incidence. Column 5 simply shows the average number of choices available over the entire journey. If we round this number to the nearest integer value (since it is not possible to have a fractional number of choices) then the distribution is as follows. The majority of subjects (23 people or 78% of the sample) had an average of three possible route choices at every junction (e.g. a classic cross road offers three choices assuming that turning around completely is not a valid option). Seven of the subjects (or 22% of the sample had an average of four choices available to them over the entire route (a junction formed by five roads).

The two final columns in the table contain information that relates to the random generator. Using the example of route 021 again, at every junction where a decision needed to be made, a random act occurred. This act was analogous to flipping a coin at a T-Junction or rolling a (tetrahedron die) at a junction of five roads, or indeed rolling a hypothetical three-sided die at a crossroad. At each node the randomly generated act is specifically tailored to that particular junction. Column 8 simply illustrates the average outcome of this random act over the entire route, whereas column 9, the last column in the table shows the angle of the road that would have been chosen by the subject if they had used the random generator to guide their decisions (which they did not). This randomly chosen angle is averaged over the whole journey in a similar manner to all the other measures.

It is then possible to compare graphically some of these values for the overall journey for all subjects. The chart in figure 6.7 opposite compares four of the values from table 6.2, plotted as a line chart.

The information in figure 6.7 represents columns 3, 4, 6 and 7 of table 6.2. Figure 6.7 shows four values that have been plotted for each of the thirty subjects. The numbers of the subjects are listed along the x-axis of the graph. The values plotted are the mean maximum choice angle available (in black), the average choice angle available (in mid-grey) and the mean minimum choice angle available (in light-grey). These values vary from person to person since they are entirely dependent on the exact route taken through the environment and not a property of the environment as a whole. However, the values for the average choice angles (mid-grey) lie approximately halfway between the mean maximum choice angles (black) and the mean minimum choice angles (light-grey), which is exactly as expected. The dotted line shows the exact choice (in terms of angle) taken by the subjects and averaged over the journey as a

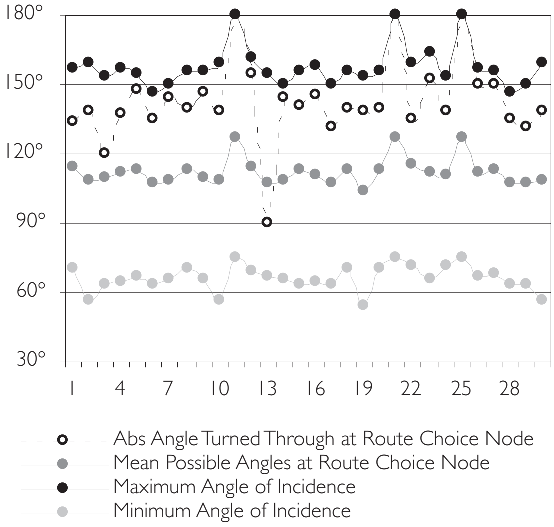


Figure 6.7 Graph of Minimum, Mean and Maximum Angles Turned through in all Routes

whole. Therefore the three solid lines represent the range of available choices, whilst the dotted line represents the choices actually taken by the subjects.

The dotted line has three principal maxima, these represent routes where the average angle of incidence chosen is approximately 180° (i.e. straight on). Since it is not actually possible to cross the 'World E' from one corner to the other by choosing 180° at every junction (since such a choice is not available), these three subjects were only able to attain such a high cumulative angle score, by walking around the edge of the world (see figure 6.8). This is precisely the strategy taken by these three subjects despite that fact that they were instructed to traverse the world diagonally from one corner to the other rather than to 'circumnavigate' it. However it serves to be a valuable illustration for the use of this method of gauging the choices made at junctions compared to the choices available.

The subjects who chose to circumnavigate 'World E' were subjects number 12, 22 and 26 (see table 6.2). There is only one subject whose angular choices were actually less than the average (the point where the dotted line dips below the mid-grey line). This is subject number 14. Essentially subject number 14 took the most undulating route of any of the sample, hence the corresponding value of their mean angular choice. Figure 6.8 opposite shows images of the routes of subject numbers 12 and 14 (namely the 'straightest' and most 'undulating' routes in the sample).

Having examined some of the particular areas of interest of the graph, figure 6.7, namely the

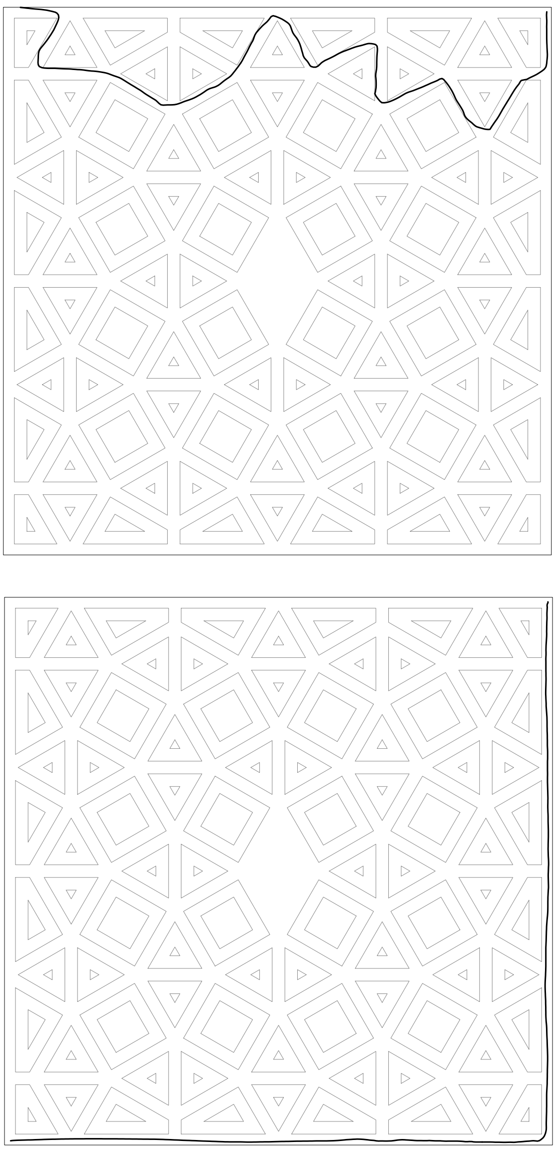


Figure 6.8 The Straightest and Least Straight Routes in the Sample

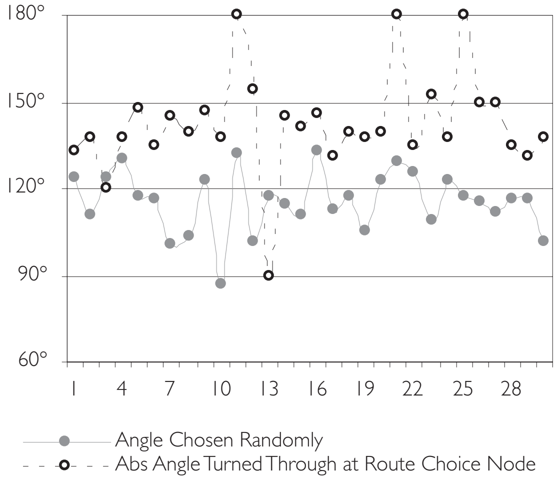


Figure 6.9 Graph Comparing Choices made by Subjects to Random Route Choices

maximum and minimum values of the individual routes (dotted), it is clear that the subjects are tending to choose roads that are on average closer to the maximum angle of incidence than to either the average or the minimum. Another way of saying this, is that as far as possible subjects are choosing routes, which tend to approximate as straight a line (the value of going straight on being 180°).

Figure 6.9 above also shows the mean angular choice value of the routes taken by the subjects (dotted line) plotted against the randomly generated route choice (grey line). The three maxima are again obvious (subjects 12, 22 and 26) as is the minimum value, subject number 14. It can be seen here that for every route excluding two (subjects 14 and 3) the routes chosen exceed the randomly chosen routes (in terms of angle), i.e. people are not only choosing straight paths, but furthermore, that this strategy appears to be the result of a deliberate rather than random process. This would appear to begin to provide evidence to support the hypothesis put forward at the beginning of the chapter, namely that that an individual subject will follow as straight a line as possible, with minimal angular deviation (from that straight line), on condition that this choice is always approximately in the direction of their goal.

Statistical Results

It is possible to examine the graphs above (figures 6.7, 6.7 and 6.9) by eye and form the judgement that it *appears* that people are making route choice decisions at junctions, taking roads which are closer to the maximum angles of incidence (measured between their approach road and their selected road) than to either the average or minimum angles. This judgement arises from the fact that the line on figure 6.7 which represents the selected angles (the dotted line) *seems* closer to the maximum angles line (the uppermost black line) than to the line representing the mean angles (the mid-grey line). However, is there a more objective method to confirm this finding, compared to subjectively scrutinising these graphs?

If the data for all nodes is considered in isolation, i.e. particular groupings of either subjects, routes or sequence are completely disregarded, then it is possible to consider simply *every* junction where *any* subject made a decision. In this way every subject/junction decision can be compared statistically against every other (regardless of other information). Over the thirty routes and thirty subjects there is data for 306 individual node decisions (this is an average of 10.2 junctions per subject, namely that any subject encountered 10.2 junctions on average over a single journey.) If the data for all these nodes is considered as a single data set, we can examine the following properties of this data: the choice taken by a subject at that junction, the maximum angular choice available, the average angular choice available and the minimum angular choice available. It is also possible to calculate the difference and absolute difference between the angle chosen and the maximum, mean and minimum angles available for choice at each node.

The first node from route 021 can, once again, be used as an example (see figure 6.5). The first decision that subject 021 was required to make was at junction 'O'. The maximum angle available to choose was 180°, the minimum angle was 90° and the average was 135°. The angle actually chosen by the subject was 90°. The absolute difference (here it doesn't matter if it is greater than or less than the angle chosen, it is simply the difference measured in degrees) between the chosen angle and the maximum angle would be (180°-90°) = 90°. The difference between the chosen angle and the mean angle would be (135°-90°) = 45° and finally the difference between the chosen angle and the minimum angle would be (90°-90°) = 0°. In this single example it is clear that the choice made by the subject was in fact closer in absolute degrees to the minimum angle than to the maximum or to the mean angles. How does this pattern change when such 'difference values' are calculated for all 306 nodes with route decision data? Since there are only 67 junctions in the world, then this data set (of 306 nodes) does not represent just one choice for every junction, or alternatively an average choice for each junction, it is the complete set of *all* choices made by *all* subjects for *all* junctions. Some junctions may have had a larger number of subjects passing through them than other junctions.

Once this node-data has been isolated from the subject/route data, for each of the 306 junctions-decisions it is possible to calculate an average value for each of the three 'difference-values'. The average, absolute difference between the value chosen at the 306 junctions and the maximum angle is 15.20°. The average, absolute difference between the chosen angle and the mean junction angle is 36.89° and finally the average, absolute difference between the value chosen at the junctions and the minimum angle is 76.08°. From this it is clear that the subjects *are* tending to choose roads which are far closer to the maximum angle than to either the average or minimum. The values are summarised below.

These statistics show that both the variance and standard deviation is less for the absolute difference between the chosen angle and the maximum angle than between the chosen angle and either the mean or minimum angles. It can also be noted that the values for both variance and standard deviation are quite similar for the difference between the chosen and maximum/average values when compared to the difference between the chosen and minimum values. This implies that the angles selected by the subjects actually lie approximately halfway between the mean and maximum values although they are slightly closer to the maximum angles.

This same information can be seen easily in figure 6.10 below, which shows the standard deviation of the difference values in degrees between the angle chosen by the subject and the maximum angle available (leftmost bar on chart) the mean angle (middle bar on chart) and the minimum angle available (rightmost bar on chart). The difference between the maximum and chosen angles is negative since the chosen angle was often less then the maximum angle chosen but greater than the mean and minimum (absolute angles were not used to generate this chart). It can be quite clearly seen on the chart, figure 6.10 below, that the standard deviation is less for the difference between the chosen and the maximum angles, than for the mean or minimum angles. Namely the standard deviation of the difference between the maximum and chosen angles is closer to zero than the other difference-values. Were the standard deviation to be zero, then the chosen and maximum values would be identical, so the closer to zero the standard deviation is, the more similar are the values.

Angular Difference Between	Mean	Variance	Standard Deviation
Selected angle & max. angle	15.20°	750.95°	27.40°
Selected angle & mean angle	36.89°	820.48°	28.64°
Selected angle & min. angle	76.08°	1387.19°	37.25°

Table 6.3 Mean, Variance and Standard Deviation of Angular Differences

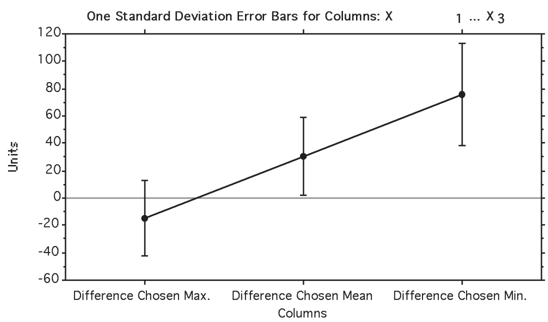


Figure 6.10 Standard Deviation Error Bars

Visualising the Measure of Angular Deviation

This section of the chapter concludes by presenting a method of visualising all the routes based upon their angular deviation value. Since there were thirty routes in the sample for which the average angle chosen over the duration of the journey can be calculated, then these thirty routes can be ranked in order of their average angle. This method of visualising the data takes these ranked-by-angle journeys and sorts them into five categories (the choice of five was made purely for the ease of assigning a simple colour spectrum (red, orange, yellow, green, blue), a finer division of category could obviously be selected).

Each category contains one fifth of the sample as ranked in order. The first fifth of the sample is then coloured red (these are the subjects who took the straightest routes possible and hence scored the highest average angle of incidence value). The second group is coloured orange, then yellow through to green and finally blue for the last fifth of the sample when ranked in order of average angle. The 'blue' sub-sample are those subjects who scored the lowest mean angle of incidence, or took the most 'undulating' routes through the world. These routes sorted, ranked and coloured-up appropriately are shown in figure 6.11 opposite.

Figure 6.11, shows the routes coloured up by their average angle. It can be seen that the first fifth of the sample (when ranked by score), i.e. those coloured red (top diagram of figure 6.11) are those subjects who took the straightest routes through the world. Most of the subjects in this sample scored so highly, either because they walked around the edge of the world, or because a large proportion of their

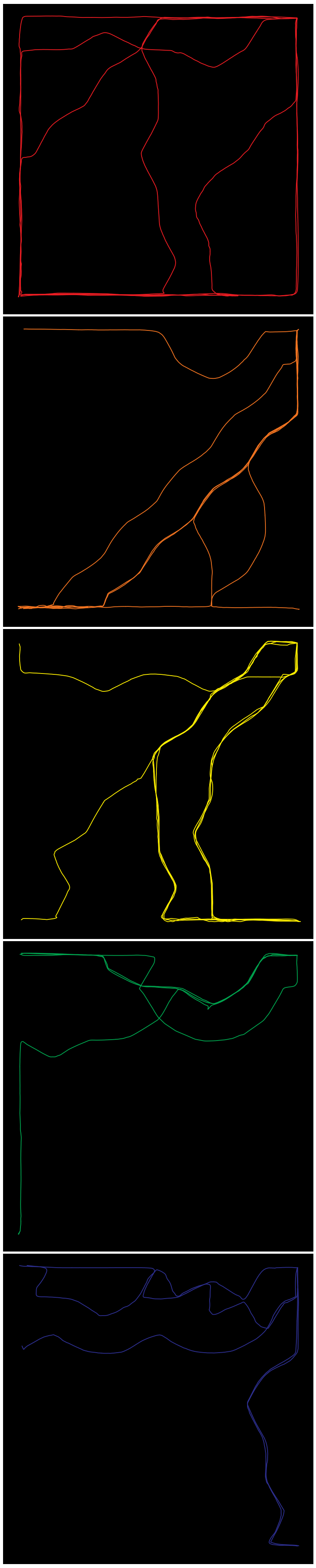


Figure 6.11 Routes Coloured by Mean Journey Angle

route included walking around the edge. The second fifth of the sample when ranked in order are coloured orange (second from top diagram of figure 6.11). This group includes the journeys that took the straightest routes across the diagonal of the world (although a couple of routes also fall into this group because a proportion of their route is around the edge, similar to the 'red routes').

The next category, is the middle fifth of the sample. This group, coloured yellow (middle diagram of figure 6.11) includes a number of routes that begin by following the diagonal quite closely (as per the 'orange routes') but then change direction, resulting in a more meandering route than the 'orange routes'. This progression from red through to orange then yellow appears to be quite appropriate and in keeping with the stated goal of visualising the 'straightness' of routes. Green is the penultimate category (the second from bottom diagram of figure 6.11) when ranked in this manner. This category begins to include some routes that are more meandering and contain turns of more acute angles (less than 90°). Finally the blue category (the bottom image of figure 6.11) includes those routes which took the most meandering and undulating paths through the world, containing the sharpest changes in angle (or least angle of incidence). Routes 14 is amongst this group (see figure 6.8). All of these routes can be viewed together, superimposed upon one another.

On the combined route diagram (figure 6.12 opposite) it is possible to identify the 'red' routes towards the edges of the world, followed by the 'orange' and 'yellow' routes along the diagonal from top right to bottom left and finally the 'blue' and 'green' routes occupying those sections of the world between the

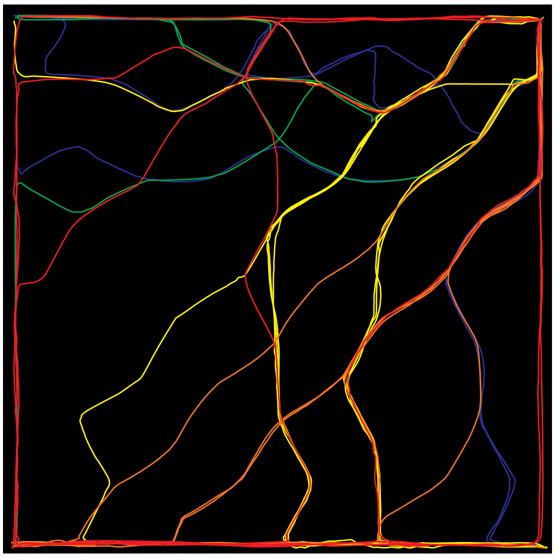


Figure 6.12 All Routes Coloured by Mean Journey Angle

diagonal and the outer edges (these being the more meandering of the routes). This method of visualising the average angle of incidence of routes, by ranking and colour coding them by their mean angle of incidence score appears to provide a useful categorisation of the routes.

This chapter has begun to examine in more detail the decisions that subjects were making at junctions and hence determining their route as a whole. However it does not begin to answer *why* a subject selects a straighter route. In order to begin to unravel what is happening at the level of the individual, it becomes necessary to examine a journey or route from the perspective of that person. Another way of saying this is that if it were possible to gauge how various environmental stimuli vary along a route, then it might be possible to determine which of these stimuli the subjects are responding to. It was noted in Chapter 1 and reinforced in Chapter 4 that there is a strong correlation between pedestrian movement flows and axial line integration. Since axial lines represent the longest and fewest lines of sight present in an environment, then it is suggested that visual properties of an environment may be influential in determining individual route choices. It is therefore proposed, in the final section of this chapter, to investigate methods of visualising how the visual field continuously varies along a route. Although no substantive conclusions will be drawn from this method of analysis, it serves to introduce the concept that what we see, or what information is visually available to us as we move through an environment may be critical to determining our actions. This is an idea that will become critical to the last chapters of this thesis.

Route Vision Profiles

In the earlier section of this chapter it was suggested that the choices made by people at road junctions appear to result in patterns of movement that are strongly linear. These linear routes also appear, 'by eye' to correlate well with patterns of spatial integration as discussed in Chapter 4. However, the question of why these decisions are being made is not clear, although subjects *must* be making use of visual cues available at the local-scale (behaviour described at the end of Chapter 4). It is proposed that by analysing the patterns of the subjects' changing visual field during their journey, that this might shed light onto the question of why subjects are making decisions that result in linear movement. One method that can be used to analyse the visual field of a subject is the generation of that subject's 'isovist' or 'viewshed' from a single point in space. An isovist or viewshed is a graphical representation of those areas of an environment that are *directly visible* from a single location or point[3] within that environment.

On the whole, the term isovist has tended to be associated with architectural applications in contrast to the term viewshed that has been predominantly used by geographers and landscape architects. In (Turner, Doxa et al. 2001) they attribute the coining of the term isovist to Tandy, which was first published in 1967. However a precursor to the current definition of the isovist can be seen to date from a series of earlier books by Gibson, (Gibson 1950; Gibson 1966; Gibson 1979). In these books Gibson gradually develops the theory that our perception of the environment is dependant upon the 'ambient optic array' available at any point. In Gibson's earliest book, (Gibson 1950) his theories of human environment perception arise from a biological description of how the image of the environment is formed on the eye's retina. Later, this book puts forward an explanation for human, visual perception of the environment in terms of 'ambient optical array'. In his last book, (Gibson 1979), he discusses environmental perception in the context of motion and tactile perception (proprioception) since he strongly maintains that the environment cannot be perceived from a stationary point in space. In his conclusion to this book, he says

> "When no constraints are put on the visual system, we look around, walk up to something interesting and move around it so as to see from all sides and go from one vista to another. That is natural vision…"

The primary difference between the viewsheds used by geographers, Gibson's ambient optic array and isovists (as they are currently used today) is that the former two are three-dimensional (or omni-planar) whereas an isovist is two dimensional (or uni-planar). This current definition of the uni-planar isovist was developed by Benedikt in (Benedikt 1979; Benedikt and Burnham 1985; Benedikt 1992).

The definition of the isovist introduced by Benedikt in (Benedikt 1979) is that the entire field of view from a single point can be represented by a planar polygon, usually parallel to the ground plane. Instead of considering the volume in which a subject stands, he revolutionises the analysis by taking a horizontal slice through the environment (usually taken at eye height). Once this visual slice has been represented by a single polygon, it is possible to apply a number of mathematical measures to the polygon. These measures include isovist area (how *much* of the environment is visible from this location?) and isovist perimeter (what *length* of occluding surface is visible from this point?). Benedikt goes onto to consider not only single isovist polygons, but also how the isovists' attributes might continuously vary throughout an environment. In order to represent this, he develops the concept of the 'isovist field', which is a graphical representation of the constantly changing values of an array of isovists. These values are represented as a contour map.

Relationships can be established between isovists and certain Space Syntax measures such as 'convex spaces' (Hillier and Hanson 1984) and 'all line' axial maps. All line axial maps are generated by producing the set of *all possible* axial lines that connect the geometrical corner points of an environment's buildings or walls. Axial lines so generated can equally be held as being the primary occluding radials for the full set of isovists generated in that environment. The all-line axial map and the set of primary occluding radials can also be seen to be related to the concept of 'e-spaces' as developed by Peponis in (Peponis, Wineman et al. 1997). Other related isovist work has focussed on the generation of isovists by a population of cellular automata in (Batty and Jiang 1999).

The route vision profile is a method for determining how individual properties of isovists vary along a route. This is not a particularly new concept, as it can be regarded as being related to Minkowski models, as illustrated by Benedikt in his paper (Benedikt 1979). It can also be regarded has having some precedent in Lynch. In his paper (Lynch 1965) he attempts to qualify the visual experience along a circular route, by graphically straightening out the route and representing it as a single line, with particularly 'interesting' views being indicated as arrows. Lynch is not using isovists (unlike this thesis), but the desire to attempt to represent the visual experience of a route through an environment prompts both Lynch's paper as well as this thesis. What is novel in the approach taken by the route vision profile is that it is not the isovist itself that is being represented, but rather how a variety of isovist *properties* might vary along a route.

The route vision profile, is a chart representation of the visual experience of a journey through an environment. The journey time (or distance travelled) is plotted in regular intervals along the x-axis of the graph, whilst the magnitude of various isovist attributes are plotted on the y-axis. The type of graph used is a line graph. The technique is illustrated using the following example. An individual journey taken through a world, for example World E, is used as the basis to generate a route vision profile. The route through the environment is shown overleaf and is an actual route taken by one of the subjects as part of this thesis' experiments.

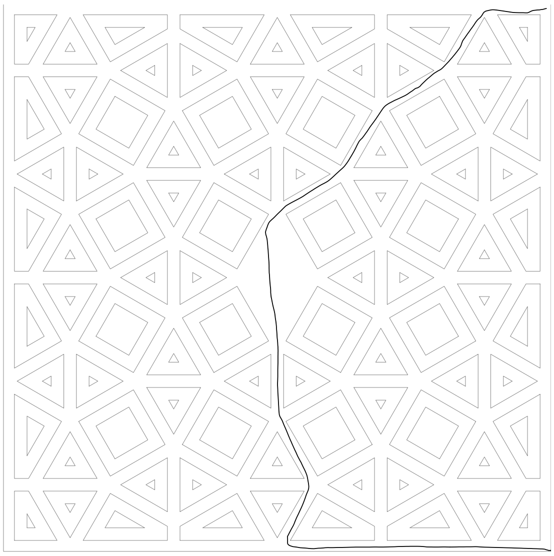


Figure 6.13 Example Route through World E

Using the application OmniVista[4] it is possible to take all points along the path and to generate as series of isovists along the route. Each location that the subject passed through will become, in turn, the viewpoint generating an isovist. Each isovist generated will have a wide range of isovist attributes associated with it, such as 'isovist area', 'isovist perimeter' and 'isovist mean radial length'. If a Space Syntax analysis of the environment has been conducted (prior to processing the route), then for each point along the path, the nearest grid-isovist location will be sought and its syntax-measure appended to the path point. In this manner, it is also possible to determine how the isovist syntax-measures vary along a route. However, the following brief examples will only illustrate how geometric properties of isovists vary along a path. The above route through World E will be used and the route vision profile generated for a couple of different isovist attributes (area and maximum radial length) presented. The route vision profile for each isovist property will be accompanied by a description of how the attributes vary along the path.

The route vision profile in figure 6.14 below represents how the isovist's attribute 'area' varies along the path taken by the subject. Examining the graph from left to right, the first peak (A) which is the same height as the last peak) represents the area of the isovist at the very corner of the world. The second peak (B) represents the first junction the subject encounters along the boundary road. The next three peaks (C) of equal height and shape represent the isovists at typical junctions in the network of streets. The wide, high peaks in the centre of the graph (D) represents the period of time that the

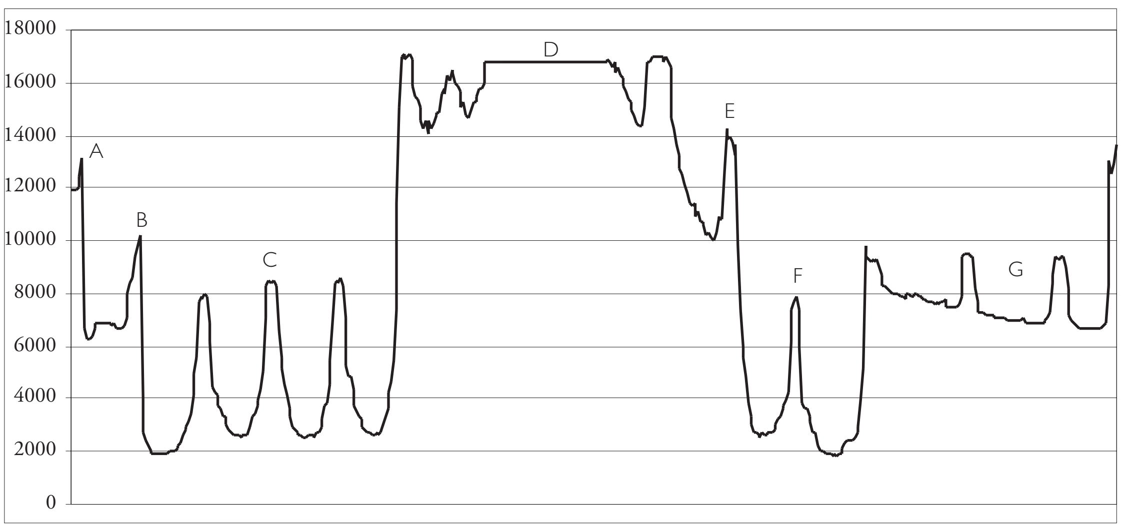


Figure 6.14 Route Vision Profile for the Isovist Attribute Area

subject spent navigating through the wide open space in the centre of the world. The next, slightly lower peak (E), represents the next junction that the subject reaches, which still has a larger than average area since there are long penetrating views through to the open space in the centre of the world (which means that this is not a typical junction). The next peak (F) is the same height as the three consequetive peaks earlier in the graph and again represents a typical junction in the network of streets forming the majority of this world. Finally the last section of this graph (G) represents the period of the journey where the subject was walking along the boundary road and each maxima on the graph represents a junction between the boundary road and a side street.

The chart below in figure 6.15 is the profile for the isovist attribute maximum radial length, which is an extremely interesting measure since it indicates the longest available line of sight from every point along a subject's path. From the graph above it can be seen that the subject could see furthest when at either the start or end point of their journey, these locations being at the very corners of the world, with long views down one whole side of the world. As the subject walks along the boundary road, the maximum distance that they can see ahead of them decreases incrementally with each step (since they are a step closer to the opposite corner). This is why the first section of this route vision profile forms a perfect diagonal line, matched by the diagonal line at the end of the graph. Once in the network of streets the subject can see less far than at any other location in the world. The peaks occur at the ends of roads (junctions) where the subject can see down the entire length of the road and the troughs occur at the centres of roads where the subjects' view is limited to half the length of the street. It is clear from the graph that the distance a subject can see increases as they emerge into the open central space, although this is still not as far as the subject's initial view or indeed the view afforded them at the end of their journey. A particularly interesting interpretation available from the route vision profile for the measure maximum radial length, is that it identifies the local-action of a subject moving along an unusually long line of sight, since this is shown as a consistently increasing or decreasing gradient on the graph. Since one of the micro-scale behaviours this

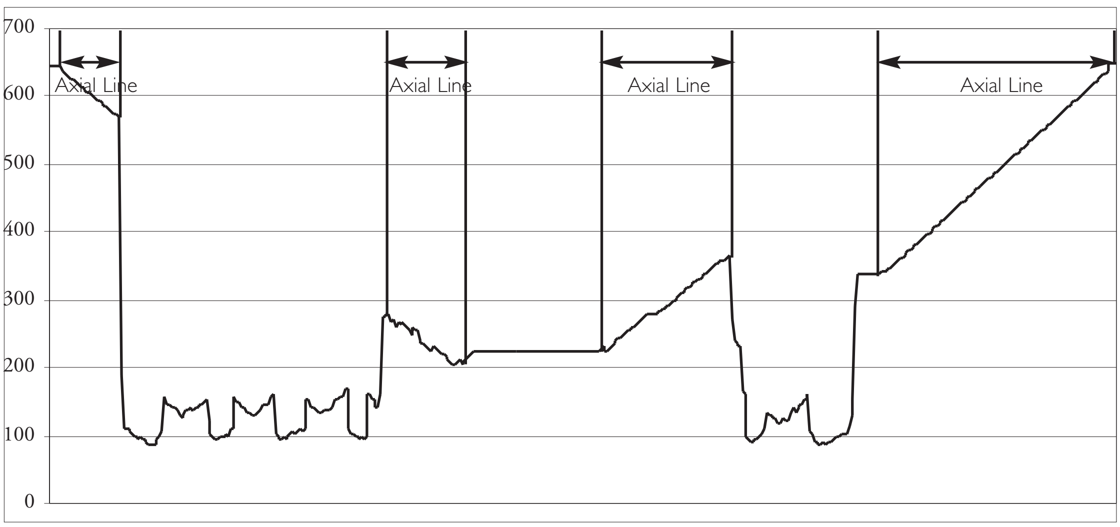


Figure 6.15 Route Vision Profile for the Isovist Attribute Maximum Radial Length

thesis is keen to identify is whether people *do* follow long lines of sight, then this method of visualisation may aid such identification.

The two graphs above were produced using a 360° isovist which was calculated at all points along the route paths. This represents the entire, *potential* view from any particular location. This would not have been the view that the subject was experiencing, since that would only be true if, at every step, the subject were to pause and look all around, before taking their next step. The human field of view is approximately 180° in the horizontal plane and this field of view may be used to generate a 'restricted view' route vision profile. The way in which this data is calculated is that at each location along the route the location of the subject is set as the viewpoint to generate an isovist (as before). Then a second item of data contributes to the calculations and this is the unit vector representing the orientation of the subject's head[5]. Instead of generating a full 360° isovist from this point, the *partial isovist* generated sweeps through a specific number of degrees set either side of the direction indicated by the unit vector. For example, this could be 90° for natural vision, 55° for headset vision, or less if a researcher were interested in, for example, foveal vision. It could even be used to examine the effect of peripheral vision, if a different type of restricted view isovist were to be generated. All the attributes that can be calculated for the full 360° isovist can also be calculated for these restricted view isovists. These attributes can then be charted in exactly the same manner as illustrated above.

In figure 6.16 below, the same path is used as an example, but this time, only the *restricted path* is generated, using a field of view of 105° (the FOV of the headset). In other words, this graph represents the visual field of the world, as the subject would have seen it. Below is illustrated the kind of graph that this type of analysis can produce.

From the example shown above it can be seen that the standard route vision profile can be particularly useful in determining how the visual and spatial properties of an environment can vary along a route. However, the 360° isovist is less useful for providing a precise record of a person's actual visual experience along a route. If the primary interest of a researcher

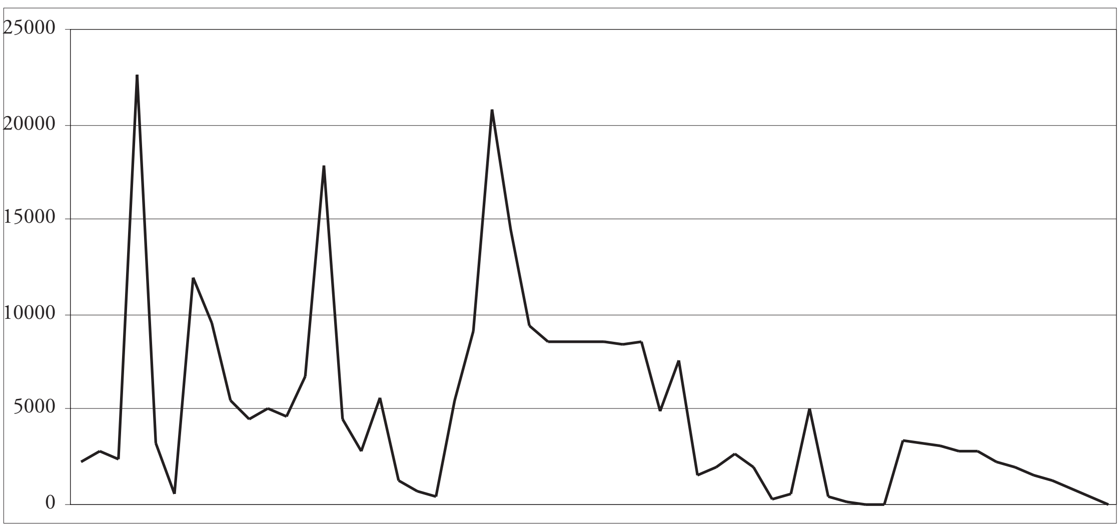


Figure 6.16 Route Vision Profile for the Isovist Attribute Area (Restricted FOV)

is the representation of the visual experience of an individual, then the restricuted path may be an extremely useful representation. Although considered to be a useful method, this technique was never applied to all of the path-data amassed during the experiments. This was because, at this stage in the thesis, it was decided that a more useful technique would be to examine what subjects looked at and to analyse the available field of view at *specific locations* in each environment; it was decided that this approach would best serve to fully answer the question of which small-scale actions are important. In order to achieve this aim, it will be necessary to alter the focus of this thesis. Instead of concentrating on 'top-down' methods (whole routes), this thesis will begin to take a 'bottom-up approach, to begin to consider individual actions that occur along a route (positional analyses). This will be the focus of the two following chapters, Chapter 7 and 8.

Key Points

- Any route through an environment can be assigned a score based upon the culmination of the decisions taken at *each* junction where it was necessary for the subject to make a route choice decision.
- For each junction along a route, the range of possible route choice decisions available can be noted and compared to the choices actually made by the subject.
- If the average decision (in degrees) made by a subject (for a single journey) is plotted alongside the maximum, mean and average angles at each junction (also averaged over the route), then the choices made by subjects appear to lie closer to the maximum angles than to either the average or the minimum.
- The choices made by subjects at junctions appear not to be random.
- The variance and standard deviation of the 'angular difference' between the chosen angle and the available angles for all 306 junction-decisions in this sample is less for the angular difference between the chosen angle and the maximum angles than for the mean and minimum angles. In other words, it appears that subjects are choosing the straightest possible routes as opposed to the more meandering or undulating routes.
- The r-squared of the absolute angle selected at any node, plotted against the maximum angle of incidence for each node is 0.342. This implies that factors other than angle of incidence contribute to route choice decisions. It is suggested that the other factor determining route choice decisions is approximate direction or heading. Namely, that subject will choose the greatest angle of incidence at a junction *on condition* that it is in the approximate direction that they are heading.
- A method of visualising routes by ranking them in order of the average angle turned through during the journey and then colour-coding them respectively, appears to provide a valuable method of visualisation, supporting an intuitive estimation of 'straightness'.
- The 'Route Profile' can be regarded as a useful tool for representing the visual experience of an individual's journey through an environment. It can take two forms, the full 360° vision or 'restricted vision' profile. The former represents how spatial and visual properties of a route vary, whereas the latter is a more accurate representation of an individual's experience of that journey.

Notes

[1] Random angles are calculated using an Excel spreadsheet.

[2] In Turner, A. (2000). Angular Analysis: A Method for the Quantification of Space. London, Centre for Advanced Spatial Analysis: 17. and Dalton, N. M. (2000). Meanda. London, Architectural Association. they both consider 'straight on' to be a zero change in angle, the opposite of this thesis.

[3] The point from which an isovist is generated is termed its viewpoint.

[4] OmniVista is an application co-authored by Ruth Conroy and Nick "Sheep" Dalton.

[5] The unit vector representing the orientation of the headset was also recorded during the experiments.

Chapter Seven:
Pause Point Data and Direction of Gaze Analysis

Abstract

This chapter will illustrate how the same raw data used to determine subject paths could also be used to calculate 'pause points'. A definition of a pause point is that it is a key location in the world where people stop or pause for a significant amount of time. The patterns formed by such pause points can be generated for different time durations. After an initial explanation of how pause points are calculated, the pause points for the seven test environments are calculated. After presenting the results of the pause points for all the worlds, a method for identifying clusters of pause points using the k-means cluster analysis is introduced. The results of the ensuing cluster analyses are then presented in full, for each world, with appropriate interpretations. Individual differences (between subjects) in patterns of pausing is explored by considering the numbers, frequency and total duration of all pauses for one of the worlds. The second half of this chapter investigates the approximate direction of gaze of the subjects while they are traversing through an environment. The first and less satisfactory method of direction of gaze analysis records the continuous direction of gaze of a subject throughout their journey. This method is superseded by a second method focusing only on the direction of gaze of a subject whilst stationary. This method of analysis effectively combines both the pause points and direction of gaze representations. Therefore, the question that emerges from this chapter is, where precisely are people pausing and what are they looking at whilst stationary? The direction of gaze analysis covered in this chapter leads directly to methods of analysing the visual fields (isovists) of these virtual worlds and their correlation to pause points. This is the topic covered in the following chapter, Chapter 8.

Introduction

In Chapter 3 and at the end of Chapter 4, the raw output data (ASCII log file) from the virtual experiments were represented as simple paths taken by individuals through the environments. This is a representation of the behaviour of a subject (or group of subjects) at its crudest and most basic level. The diagrams at the end of Chapter 4 purely illustrated *where* people had travelled. Earlier in this thesis it was suggested that this could be regarded as a 'top down' approach to answering the question of which small scale actions might be important in the production of observed patterns of real-world movement. This chapter begins to make a shift from examining continuous routes and begins to investigate what individual actions may be yielded by the same data. Tactically this can be held to be a 'bottom up' approach to the same question; the focus of this chapter is upon smaller-scale actions not routes.

In Chapter 3, as part of an explanation of how the first routes were visualised, a list was presented which suggested the type of additional information regarding a subject's journey that it could be possible to extract from such data. This information was as follows:

- Continuous path of movement of any person
- Location of a person at any moment of time
- Location of a person's 'Pause Points' or 'Dwell Points'
- Number of a subject's 'Pause Points' or 'Dwell Points'
- Proportion of the journey spent stationary by any person
- Total distance travelled & total journey time
- Average velocity/acceleration over the journey
- Continuous locus of the orientation of the head mounted display
- Approximate direction of a subject's gaze whilst stationary

The first two items on this list have effectively been covered in the proceeding chapters. This chapter will illustrate how it is possible to calculate and represent the majority of the measures listed above. This is an example of one technique for moving from the macro level (the movement paths) to the micro level of smaller scale behaviours that take place en route.

The Calculation of Pause Points

In considering individual actions such as pausing behaviour, the questions that are prompted are where precisely along a journey does a subject pause, at what kinds of locations does a person stop and for how long? In order to calculate pause points from the original log file data it was necessary write a small computer programme[1]. This programme was based upon the earlier application that transformed the raw ASCII log file into a 2d CAD representation of the paths. However, it was necessary to adapt and extend the original programme to calculate where people were pausing in the environment and to represent these locations as a 'point' on plan. These points are the graphical indication of pause points or dwell points.

How are these dwell points calculated from the log file? The raw data are simply series of points in space that are occupied by a subject and ordered chronologically. The first stage is to compare each sampled position to its neighbouring locations (in the list) and to calculate the distance moved by the subject between every two consecutive sampled points. If that distance is zero, then the subject has been stationary between those two sample-points. By comparing each world location in the list to the preceding and following positions to record any locations of zero movement, a separate sub-list of dwell points can be compiled. This is only the first stage. It then becomes necessary to define what is actually a *deliberate* pause and what might be simply a momentary hesitation, caused, for example, by a finger slipping off the 3D mouse. If a person pauses for a fraction of a second, should this be counted as a dwell point? The next stage, therefore, is to establish a *lower limit* below which a person is not held to be deliberately pausing. There is no need to establish an upper limit; a person will simply remain at the same location until such time they decide to move on. It is the lower-limit time 'trigger' that is the most important criterion to establish.

A decision must be made to determine which time 'trigger' is to be used, such that any pause *longer* than this amount be counted as a deliberate pause. The strategy used to determine which time triggers were significant was to initially calculate ten-second, five-second, two-second and one-second pauses for all worlds. Note that, in this thesis, the phrase 'x-second pause' indicates that the total duration of a pause point can be any length of time longer than and including x seconds. The results of calculating a range of pause points for all worlds were that there were almost no occurrences of ten-second pauses and relatively few five-second pauses (other than at the start and finish locations). In contrast, in most worlds there appeared to be an unwieldily high number of one-second pause points. For most worlds, the number of two-second pause points fell approximately midway between the totals of one and five-second pauses and intuitively it seemed that this time interval was the optimal one to use for the majority of the environments. Unless stated elsewhere, this is the pause point duration being calculated. It may seem as if this is a very brief interval of time, but it is suggested that conceivably such duration feels longer in a virtual world than in the real world. It could be that a two-second pause might be analogous to a much longer pause in a real environment and this could be a useful area for future research.

It should also be stressed once again that this time duration is, in fact, the *minimum* time interval recorded and that many subjects were in fact stopping for periods far exceeding this amount. Figure 7.1 below shows a typical world, World C and the path of a single person superimposed by their two-second pause points, indicated as points along their route.

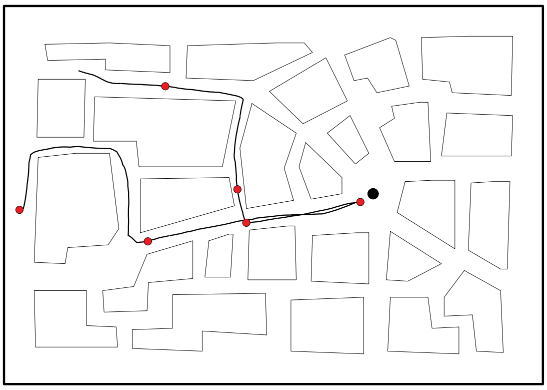


Figure 7.1 A Single Route with Pause Points

After calculating and representing the patterns of pause points for *one* subject in an environment, the aggregate patterns of all pause points for all subjects in each world can be produced. This was achieved by superimposing all pause points for all subjects on the same plan. On calculating the aggregate patterns of pause points for all seven worlds, it was eventually decided to use different durations of pause points for some of the environments (although two-seconds is still the predominate time-duration used). Unless stated otherwise, the pause point duration is two-second. However, whenever a decision was made to use alternative pause point durations, full explanations for the reason are given alongside the interpretation of the results (in the following section). A summary of the pause-point durations for the different worlds is given in table 7.1 below.

World	Pause Point Duration (minimum limit)
World A	5 second
World B	2 second
World C	2 second
World D	2 second
World E	0.5 second
World F	0.5 second
World G	0.5 second

Table 7.1 Pause Point Durations for all Worlds

Patterns of Pause Points in the Experiment Worlds

The following set of figures shows the patterns of pause points for all subjects in all seven, test environments. An explanation of the results are given, discussing each world in turn.

World A, The Tate Gallery

In World A or the Tate Gallery, the pause points illustrated above are calculated at five-second instead of two-second intervals. There were a far greater number of two-second pause-points in this world compared to the other six worlds. It was for this reason a longer time interval was used. It would appear that we may move at a different pace in a building

$$\left(\frac{Total\ Duration\ of\ all\ Pause\ Points}{Total\ Duration\ of\ Whole\ Journey}\right) = Propo$$

Figure 7.2 Pause Points in the Tate Gallery

than in an urban environment, even through these environments are only simulated. It would be logical that the difference in scale between buildings and urban environments could produce differences in patterns of stopping behaviour. A time interval that constitutes a significant pause at the building level may not constitute a significant pause at the urban level.

It is initially conjectured in this chapter that people could be pausing at locations where route choice decisions need to be made. At the urban level, these locations are obviously road junctions. At the building level analogous locations could be the thresholds between adjacent spaces, such as doorways. In which case it could be expected that subjects should be pausing in or in close proximity to doorways. Although some pause point locations near doorways can be observed, this does not seem to be the overall pattern of locations. Quite often, a subject appears to be stopping in the centre of the room and looking around. However, this behaviour may be attributed to the scale of the environment. At the urban level, where junctions are often situated at a considerable distance from other junctions, it is not unusual to be unable to see around a corner until quite close to a junction. In complete contrast to the urban experience, due to the smaller scale of a building, it is possible to stand in the centre of a space and on scanning the room, to catch penetrating glimpses through a *number* of doorways simultaneously, namely that in a building it is possible to survey multiple route options simultaneously in a manner quite impossible at an urban level (assuming that doors are open).

It can also be noted that there are a large number of pause points in close proximity to the subjects' starting position, at the main entrance (the bottom, middle on plan). The density of pause points remains high in the vestibule beyond the entrance lobby and only begins to fall off after this second entry space.

World B

In World B, the subjects all started their journeys in the uppermost, left-hand corner, on plan. The exact location of their starting position was in the centre of the open 'square' formed between the corner of the boundary wall and the concave corner of the adjacent cruciform block and there are a large number of pause points situated around this area. It soon became clear that it was usual for a subject to remain stationary upon first entering a world, whilst they looked around in order to both acquaint themselves with and orient themselves to the environment. Another obvious location for pause points is the centre of the world, which is, in this particular case, also the wayfinding goal. Again, it appeared to be quite common for subjects to pause to scrutinise the monument upon reaching their goal, perhaps to confirm that they had really reached their destination. Apart from these two patterns of stopping, the only characteristic shared by the pause point locations in the other worlds is that they appear to be in close proximity to road junctions. The relative density of pause points is greatest along the primary route from the starting location to the wayfinding goal and in direct proportion to the distance from the starting location, namely that early on in a subject's journey they appear to be more inclined to pause momentarily (perhaps whilst familiarising themselves with the controls).

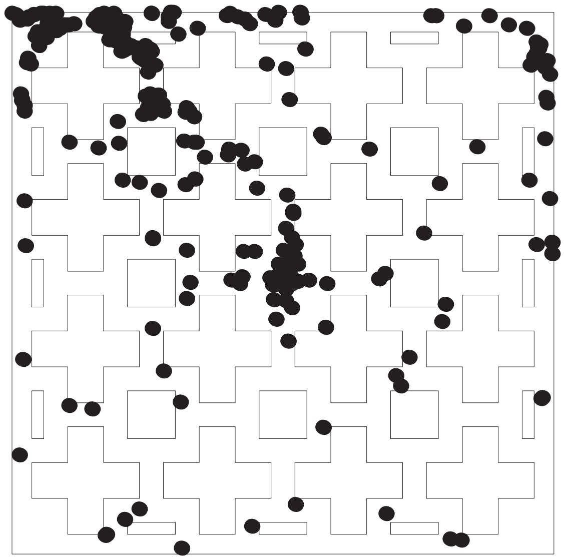


Figure 7.3 Pause Points in World B

World C

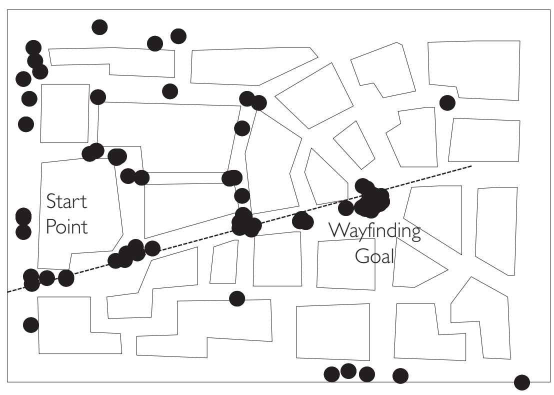


Figure 7.4 Pause Points in World C

In World C, the subjects start their journeys at the middle, leftmost side of the plan view. This location is marked by a number of pause points, which appear as only one or two points, since they are coincident. A large grouping of pause points is evident around the monument, in the central 'square'. This was the wayfinding goal used by the subjects. Again, there is a greater number of pause points scattered along the most direct route from the starting position to the monument, namely the straight, diagonal route to the lower half of the plan view (indicated with a dotted line). Again, the locations of the pause points appear to be distributed in close proximity to road junctions.

World D

In World E, the subjects started their journeys in the same location as the previous world, World C. As in World C, there are also a large number of pause points located around the monument. There appears to be fewer pause points in this world, spatially distributed more evenly throughout the environment. Again, it does appear that subjects are pausing at or close to road junctions. At first, it appears puzzling that people are pausing less in the more unintelligible and potentially more confusing world. It could be expected that subjects would pause more frequently, the more disorientated or lost they become. Instead, the opposite appears to be happening, as subjects become disorientated they pause less. It may be that subjects are pausing only in locations that afford them maximum environmental information. If a subject is lost in a segregated, visually limited part of an environment, they do not pause to look around. Instead, they continue until they emerge into a more integrated, larger space, at which point they then pause to take stock and re-evaluate their route-choice decisions. It then follows that subjects would stop less not more in an environment that was intrinsically confusing (i.e. unintelligible).

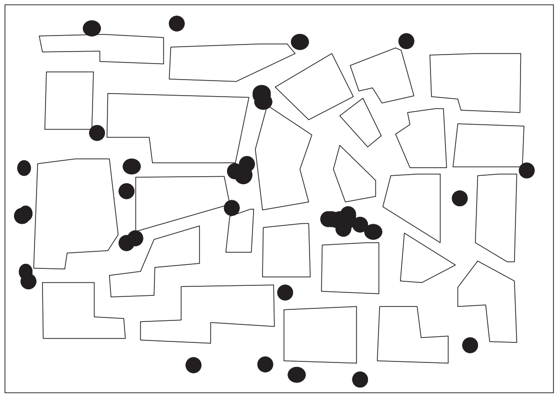


Figure 7.5 Pause Points in World D

World E

Worlds E, F and G were the last experiments to be performed. Due to problems with the equipment set-up, by this stage, many of the subjects were feeling slightly nauseous. In order to enable these subjects to complete the experiment, all subjects were shown how to accelerate their pace, enabling them to move at a faster pace. (See Chapter 4 for a fuller explanation of the experiment procedure.)

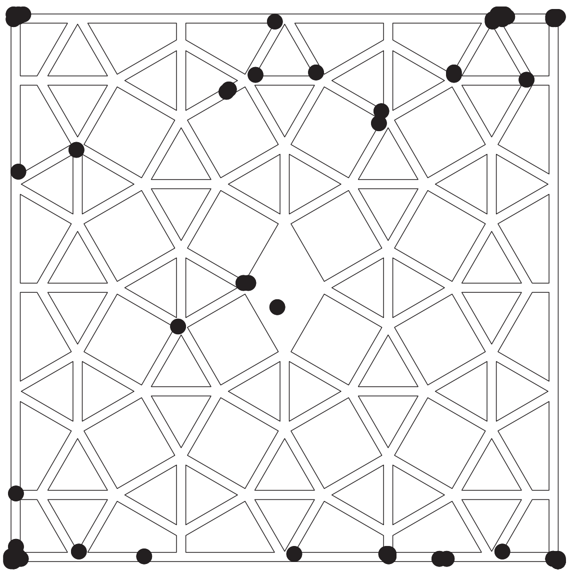


Figure 7.6 Pause Points in World E

Surprisingly, the patterns of pause points for these worlds seem to reflect the increased pace. Since the subjects were moving at a faster speed, they appeared to pause less often and for smaller time intervals. On subsequent calculation, there were very few two-second-pause points and therefore it was decided to attempt to calculate half-second pause points instead. The resultant pattern of half-second pause points appears to follow the expected pattern for longer pause points, based upon the results of the other worlds. The patterns of stopping behaviour for worlds E, F and G use half-second pause points rather than two-second pause points for their calculations. This ensuing behaviour had not been anticipated during the experiments, the increased pace having only been introduced as an impromptu measure to ensure the completion of the experiments by all subjects. However, both Worlds E and F appear to confirm the observation that subjects appear to be pausing at locations where a route choice decision needed to be made. It also appears that this pattern is more marked in these two worlds than in any of the other worlds. See World F results in figure 7.7 below.

World F

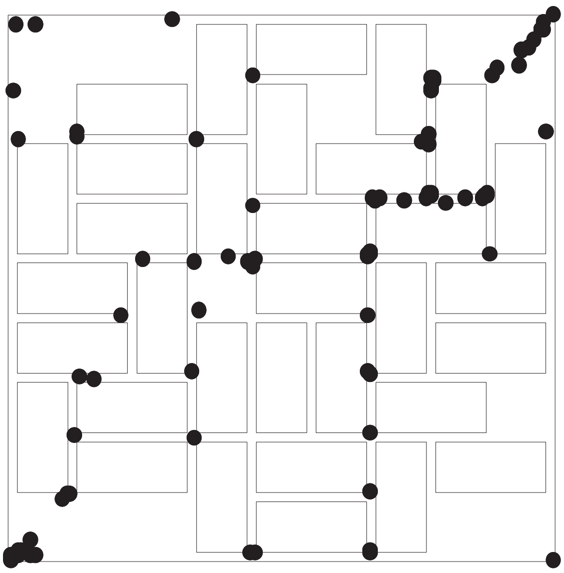


Figure 7.7 Pause Points in World F

World G, Barnsbury

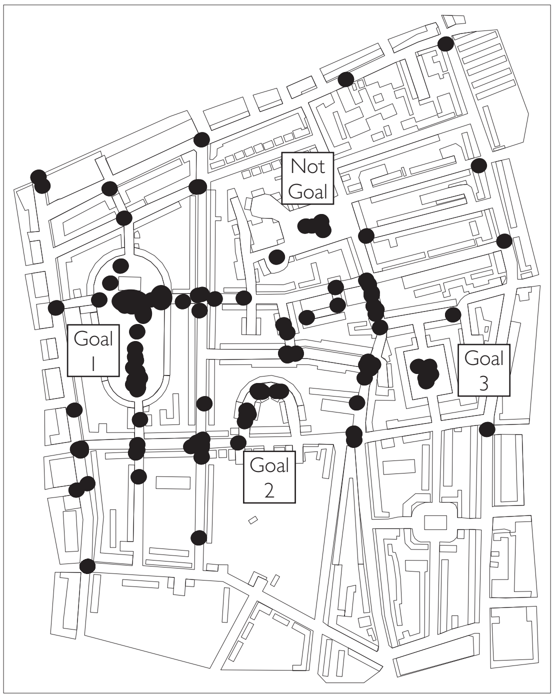


Figure 7.8 Pause Points in World G

In Barnsbury, all subjects began their journey in the bottom-leftmost corner, marked by what appears to be a single pause point (in reality a large number of coincident pause points). There are clearly a number of pause points clustered around the three wayfinding goals, goal 1, 2 and 3 on the plan (the keyhole shaped 'square', the crescent and the square). Another square (also marked on the plan, in the upper, rightmost quadrant) proved to be quite a popular place to stop. Many subjects paused here to determine if they had found goal 3. If points lying outside the areas marked as either goals or potential goals are considered, it can be seen that most of these locations also appear to be located in or close to road junctions. This is entirely in keeping with the results found in all of the other experiments.

All these worlds appear to confirm that people are pausing, in the main, at locations where a route choice decision needs to be made. This would be quite a 'common-sense' finding to present. It would be logical to conclude that this should be the behavioural pattern of groups of subjects within an unfamiliar environment. However, this is purely an initial interpretation based upon a visual presentation of the subjects' pause point locations. In order to make a more accurate assessment of the patterns of people's stopping behaviours, a more accurate method of determining these patterns must be devised. Since it would appear that people *might* be responding to visual cues, then a method of interpreting this pause point data could be developed using isovist analysis. This is covered in the following chapter, Chapter 8.

Pause Point Cluster Analysis

In the previous section, it appeared that there were identifiable groups of pause points. In most worlds, subjects appeared to be pausing at the start of their routes and upon reaching their wayfinding goals. It was also conjectured that subjects appeared to be pausing near or in close proximity to road junctions. Alternatively, as in World A, it was suggested that subjects appeared to be pausing at the centres of rooms. Since this thesis is concerned with which small-scale actions might be important, then the identification of *any* consistent patterns in subjects' pausing behaviour could contribute to an understanding of how small-scale actions produce the emergent phenomenon which is pedestrian movement. The question is, do clusters of pause points occur more in some regions of the world than in others?

In order to determine whether or not there might be any clustering pattern to the location of the pause points, it was decided to perform a form of cluster analysis on each aggregate set of pause points. The method used is a relatively simple method of cluster analysis termed k-means clustering; k-means is a straightforward and efficient process of establishing clusters using an iterative algorithm.

The K-means Clustering Algorithm

This algorithm was first developed in 1967 by MacQueen. The k in k-means indicates the number of clusters to be found. This is usually established before any calculations are made. The k-means algorithm is an iterative algorithm that means that it will run repeatedly until a solution is found, generating more accurate approximations to the correct answer each time.

Imagine a number of data points. Let the total number be n. The number of clusters, k, is first established (i.e. k must be given a value before the algorithm can run) and it is essential that $k \leq n$.
A number of data points are chosen randomly from the sample, this number being equal to the number of clusters being sought. For example if there are one hundred points in the data set and an attempt is being made to seek five clusters, then five points are chosen at random from the original one hundred. Each one of the randomly chosen points acts as the centre of a 'proto-cluster'. The centre of a cluster is the mean value of all the points or,

$$Centre(x, y) = \left[\sum\left(x^{1}, x^{2}, x^{3} \ldots x^{m}\right)/m\right], \left[\sum\left(y^{1}, y^{2}, y^{3} \ldots y^{m}\right)/m\right]$$

Equation 7.1

where m is the number of points in a given cluster.

This can be held to be analogous to 'seeding' the clusters. A test is then performed. The Euclidean distance between each point in the data set and each of the k number of cluster centres (the randomly chosen points) is calculated. When the centre closest to a point is identified, it results in the point becoming a member of that cluster. This process is continued until each of the data points is a member of one of the k number of clusters. All points must be assigned to a cluster. When this stage has been reached a new centre for each cluster can be calculated based upon the mean location of all the data points forming each cluster. A new set of cluster centres is then calculated (as opposed to being randomly assigned as in the first example). The whole process of determining which is the closest cluster centre is then repeated, with the data points being re-assigned. Some points might become members of alternative clusters.

Each time this process is repeated, the new cluster centres are calculated (and new clusters formed). However, each time a new centre should be slightly closer to its old centre (and this distance should keep diminishing with each iteration), until finally there is no change in location between one cluster centre and its previous or subsequent centre-locations. When the cluster centres have settled down to a stable state the k-means algorithm has been completed. This is why it is termed a 'self-organising' algorithm.

The only difference between the implementation of the algorithm described above and the one used to produce the following clustering diagrams, is with regard to the assignment of k, the number of clusters. As stated above the first stage in the k-means calculation is usually to decide how many clusters are being formed. In the statistical package, Datadesk, used for these examples it calculates all possible numbers of clusters from 1 to n. It is possible for a point to be both a member of a cluster of 1 (it is a cluster on its own) and hence there are n clusters, or for a point to be a member of one giant cluster with all other points as co-members and no other clusters. All other possibilities in between are also calculated. The results are presented as a tree diagram.

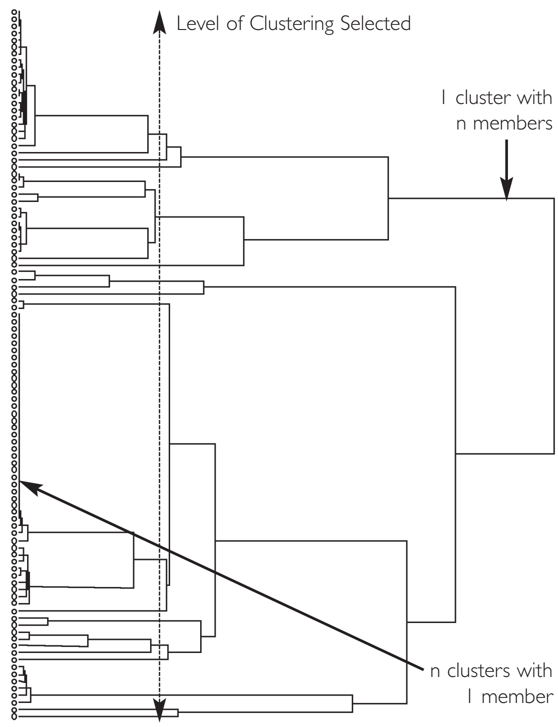


Figure 7.9 Cluster Tree Diagram

By using the tree diagram above, a level of clustering was selected (by eye), that was neither too extreme (in either direction). This stage is indicated by the pointed section line marked on the figure above.

The results of the k-means clustering analysis, performed on each of the seven virtual worlds are presented overleaf.

World A, The Tate Gallery

Figure 7.10 Pause Point Clusters in World A

World B

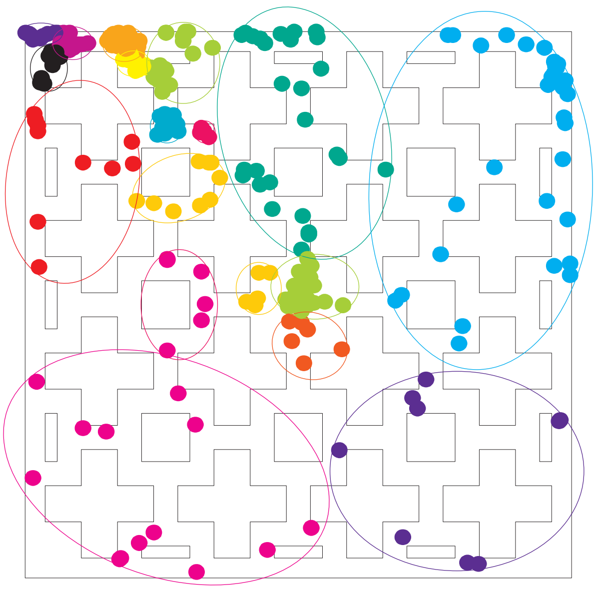


Figure 7.11 Pause Point Clusters in World B

World C

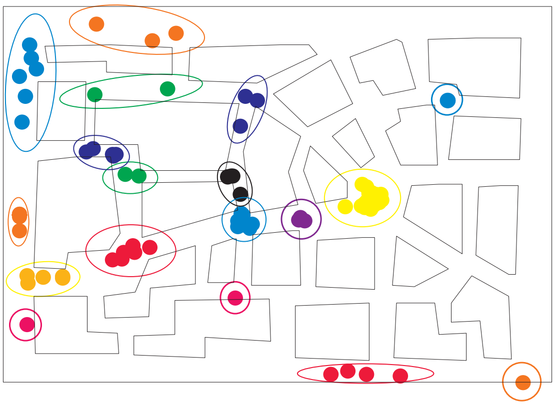


Figure 7.12 Pause Point Clusters in World C

World D

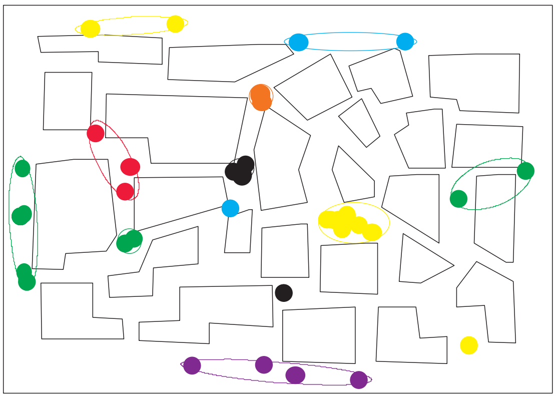


Figure 7.13 Pause Point Clusters in World D

World E

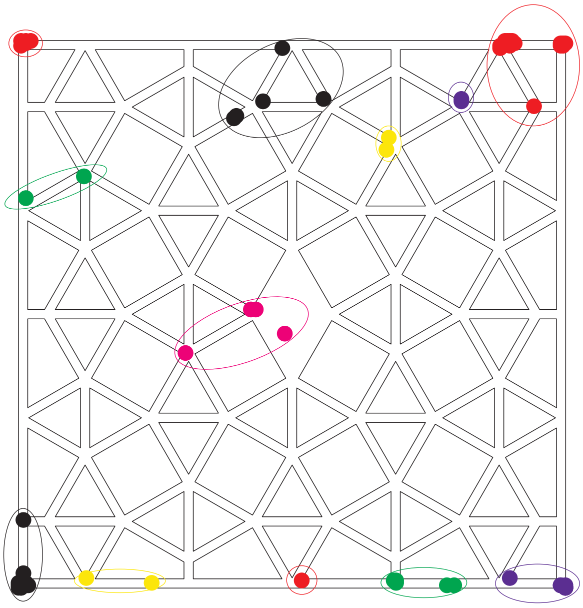


Figure 7.14 Pause Point Clusters in World E

World G

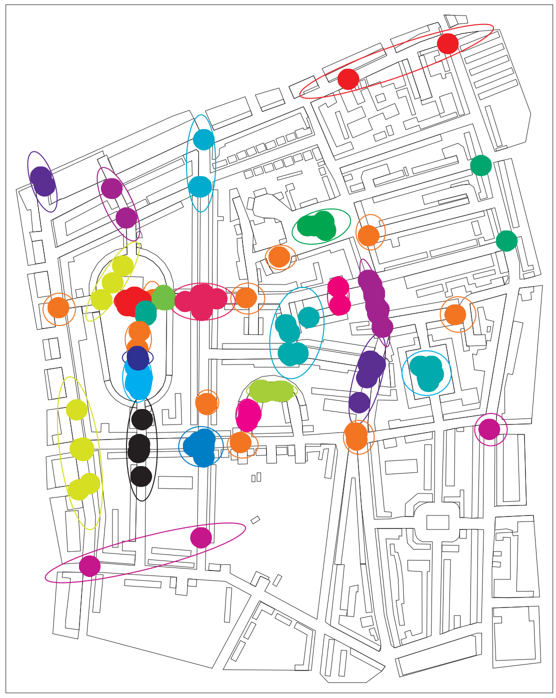


Figure 7.16 Pause Point Clusters in World G

World F

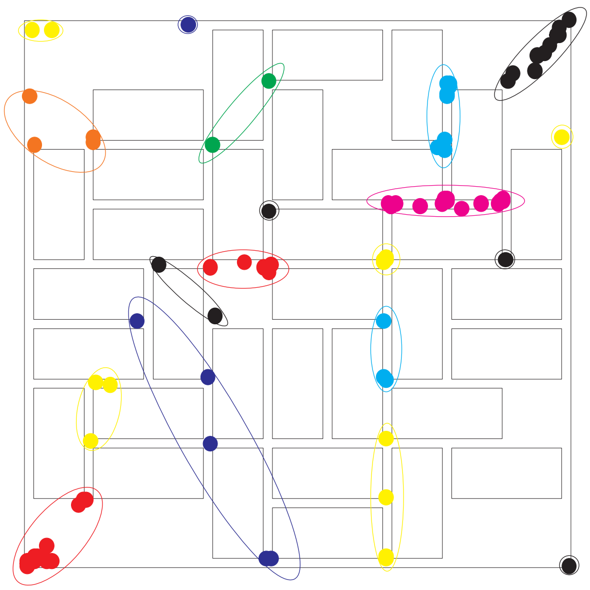


Figure 7.15 Pause Point Clusters in World F

There is no need to provide additional descriptions of the clustering diagrams above, since they are quite self-explanatory and any descriptions would only mirror those provided alongside the basic (non-clustered) pause point analysis in the previous section.

Considering all the pause point clustering diagrams above, the k-means algorithm appears to be quite effective at identifying clusters; it frequently identifies clusters of points, which intuitively one would have identified by eye. In this manner, it could be used to automate the analysis of pause point patterns and could be used to calculate the centre of a group or cluster of such points. However, in this particular data set, it does little to highlight any patterns not visible to the eye; it serves only to support one's intuition rather than augment it in any way. In many respects, it would appear that the value of such a method of analysis rests in the interpretation of the results. In this particular case, any interpretation would simply mirror the initial descriptions of the patterns of pause points given in the previous chapter section. This is not to say that using a type of statistical cluster analysis *only* mirrors our intuition. There are occasions when patterns not visible to the eye can be highlighted or identified by using this method. It is simply that in the examples shown above, this method of analysis seems to shed no new light onto the results.

Occasionally, in the above examples, the cluster analysis identifies a group of points which, considered against the urban street or building configuration, appears to be counter-intuitive. Since k-means cluster analysis *only* uses the co-ordinates of the pause points and does not take into account the urban/building structure in any manner, it is questionable how useful a method of analysis it is. The algorithm will sometimes identify a cluster of points, which in reality is quite meaningless. Clearly, when taken in context, certain pause points may have nothing in common whatsoever. This flaw could be easily rectified by adapting the k-means clustering algorithm to include spatial information. Currently a point is assigned to a cluster based purely upon its distance from that cluster's centre. However, a second condition for joining a cluster could be introduced. A point may join its nearest cluster if the centre of the cluster is visible from that point. If not, it is assigned to the next nearest cluster (providing its centre is visible) and so on. If no clusters are visible to a point, it becomes a new proto-cluster in its own right. In this way, although a number of clusters would need to be pre-defined before running the algorithm, it would be impossible to predict how many clusters would actually be formed once the algorithm had reached a steady state.

In conclusion, if the string matching algorithm presented in chapter 5 is a way of looking for patterns or similarities amongst a sample of routes, then cluster analysis can be regarded as performing an analogous task for pause points. Although each method is presented in a rudimentary manner in this thesis, there is a need to develop a set of more sophisticated tools to enable this kind of pattern recognition. If it is to be possible to calculate how aggregate pedestrian movement arises from a number of small-scale actions. It is not only necessary to be able to observe and identify these actions, but more importantly to seek patterns and similarities amongst them. The work presented in this chapter and chapter 5 can be regarded as first steps towards this goal.

Numbers of Pause Points, Travel Distance & Proportion of Time Spent Stationary

Other patterns might be found in the distribution of pause points. Instead of examining how the pause points are *spatially* distributed in an environment, it may be possible to discover other relationships in the number or frequency of pause points over a single journey. This could lead to other questions, such as, can similarities be found between various groups of individuals? Therefore, the next set of information to be extracted from the log files, is the total number of an individual's pause points. These can be correlated to the proportion of a journey that is spent stationary by any person and to either the distance travelled by a person or their total journey time. A single example of this type of data analysis is worked through to illustrate how it may be analysed in this way.

If we use World B as the example, it is possible to take the log file and process it in order to extract the number of pause points for each subject. One hypothesis raised by this form of analysis is that in an unfamiliar environment, where a subject does not have prior knowledge of their route, they might be likely to pause more frequently during their journey. In this world, the least number of times that a subject paused was twice, the greatest number was twenty and the mean number was 9.4 times.

The development of methods to analyse these dwell points may potentially provide additional information on how a subject navigates through an unfamiliar environment. In particular, analyses of both the location and duration of these dwell points might illuminate which aspects of an environment the subjects uses to aid such navigation.

Duration of Dwell Points

To examine the amount time spent stationary by each subject in World B, this method selects the *proportion* of time spent stationary for analysis, in preference to the total amount of time spent stationary (measured in numbers of points sampled[2]). In a long journey, it would be expected that the amount of time spent stationary would be greater, since the entire journey time itself is greater. The proportion of time spent stationary, is independent of the journey time, since it considers the length of journey. The proportion of time spent stationary, can be calculated as follows.

$$\left(\frac{Total\ Duration\ of\ all\ Pause\ Points}{Total\ Duration\ of\ Whole\ Journey}\right) =$$

$$Proportion\ of\ Journey\ Spent\ Stationary$$

Equation 7.2

This method also has the advantage that by using proportions the result is dimensionless. It does not matter if the calculations are done using numbers of samples or seconds, since the result is identical

In the sample of 36 people undertaking the I.C.A. experiment, the minimum amount of time spent stationary by any subject was 11% and the maximum amount of time spent stationary was 70%. The mean amount of time spend stationary by all subjects, as a proportion of the total journey length, is 26%. Ttable 7.2 overleaf contains the tabulated data of these calculations. Once the percentage proportion of time spent stationary has been calculated for each individual subject, this data may be plotted against the total journey length.

All subjects were given the same instructions, namely to locate the monument at the centre of the virtual world. Therefore, it can be assumed that those subjects who found the monument very easily were those who took the most efficient (most direct) route. It can also be assumed that these subjects would also have the least journey distance, as measured in metres. Conversely, this implies that subjects who became the most lost and encountered the greatest difficulties in finding the monument were the ones who took the least efficient routes and had the greatest journey distance.

The comparison of the percentage of journey time spent stationary to the total journey length measured in metres can be used to test a hypothesis. The hypothesis being tested is that the more lost a subject becomes they more they pause to try to work out the correct route. If this hypothesis were correct, then there would be a positive correlation between the length of journey time and the proportion of pause points. In fact, if we examine the data from

Subject Code Number	Journey Duration / Number of Samples	Duration Spent Stationary / Samples	Total Number of Stationary Locations	Distance Traveled / Metres	Proportion of Journey Stationary
1	729	131	8	409	0.18
2	868	208	7	112	0.24
3	836	202	15	439	0.24
4	1086	194	9	647	0.18
5	536	165	5	218	0.31
6	677	337	6	227	0.5
7	570	84	6	350	0.15
8	558	292	12	181	0.52
9	1214	401	18	512	0.33
10	780	260	20	316	0.33
11	486	124	10	234	0.26
12	1180	181	10	682	0.15
13	446	180	8	179	0.4
14	437	130	11	190	0.3
15	1030	719	4	210	0.7
16	1276	137	10	799	0.11
17	1141	276	19	574	0.24
18	1273	188	12	785	0.15
19	431	131	6	202	0.3
20	750	104	9	291	0.14
21	797	196	12	399	0.25
22	436	48	2	267	0.11
23	681	75	5	329	0.11
24	481	153	10	195	0.32
25	425	102	3	209	0.24
26	461	99	8	212	0.21
27	1057	121	13	659	0.11
28	664	347	19	201	0.52
29	443	85	4	246	0.19
30	355	93	5	179	0.26
31	505	58	3	275	0.11
32	596	81	7	358	0.14
33	692	263	19	254	0.38
34	787	129	5	459	0.16
35	917	243	12	410	0.26
36	440	73	6	251	0.17

Table 7.2. Tabulated Dwell Point Data

World B we find the complete opposite. Rather than a positive correlation between the two, we find a negative correlation, namely that those subjects who became more lost, were those who paused least to find their way. In the following section the data and scattergrams will be examined in detail in order to discuss why this may be so.

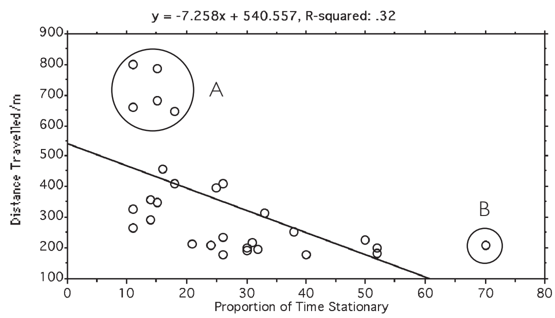


Figure 7.17 Scattergram of the Relationship between the Proportion of a Journey spent Stationary and Distance Travelled

If we consider first the five points circled on the upper top left hand corner of the scattergram, we find the mean proportion of time spent stationary by these five individuals is 14%, comprising of measures of 11%, 11%, 15%, 15% and 18% respectively, i.e. these subjects had some of the shortest dwell point durations of all of the subjects in the sample (11% is the least proportion spent stationary of all subjects). These same five subjects[3] also took a significantly longer time to reach their goal, measured in distance travelled. There are no other subjects who took longer or more circuitous routes to the monument. It appears that those subjects who found their goal most efficiently, i.e. by traversing the least distance to get there, were also those who paused the most.

It was not found that subjects who became lost compensated for their disorientation by pausing more frequently to find their way. Rather, it can be conjectured that those subjects who had most difficulties finding their goal, did so *precisely* because they paused infrequently and hence potentially missed vital visual clues indicating the correct route. In fact, by inspecting the subjects' routes on plan, at least two instances can be found, where subjects passed within sight of the monument. They would have seen their goal if they had only paused to look around but instead they moved past, evidently missing their goal.

If we now return to the scattergram and examine another anomaly, there is a single point, circled on the bottom right hand side of the scattergram. Here we find a subject who spent a disproportionate amount of time stationary. In fact, this particular subject spent 70% of her time stationary. We can also examine the data and extract the number of locations this subject paused; the subject only paused in four locations. (The average is 9.4 times for the whole sample.) What personal information might explain the behaviour of this individual? The subject was female and was the oldest person to undertake the experiment; her age was 52 (the mean age of the sample was 33 years). In contrast to the other subjects, she also reported that she experienced feelings of dizziness and nausea and that she consequently had problems navigating. In conclusion, many factors about this subject's personal information and experiences of the experiment appear to be very different to the group of subjects as a whole. If we exclude this subject from the sample and plot the new scattergram, we find a slightly tighter correlation. See the f igure 7.17 below.

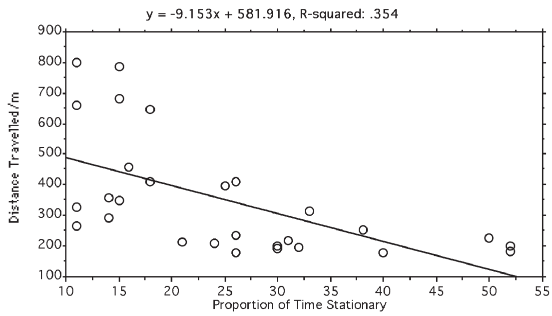


Figure 7.18 Scattergram of the Relationship between the Proportion of a Journey spent Stationary and Distance Travelled

In conclusion, it appears that there is a slight negative correlation (r2 of 0.32 or 0.354 excluding the subject who spent 70% of her time stationary) between the proportion of a subject's journey time spent stationary and the length of their journey measured in metres. Another finding of this method of data analysis is that this method can potentially be used to identify subgroups of subjects. This can be achieved by identifying similarities in subjects' spatial behaviour (i.e. all of them getting lost yet hardly pausing to consider their environment). It may be that with a much larger sample size and using different test environments, it may be possible to identify many more subgroups of people based on common spatial behaviour. This could be a valid area of future research, but is beyond the scope of this present thesis.

Direction of Gaze

Since it appears that subjects may be pausing at junctions, at locations where they have to make a route choice decision then an examination of their approximate direction of gaze might afford an insight into which visual cues are contributing to subjects' decision-making process.

Up until this stage in the chapter, all methods of analysis and representation have been calculated using the first three values in the log file, (see page 53, for an example of a log file), the x y and z location of the subject, at any instant of time. The following two techniques for investigating micro-behaviours en route, use the final three values. These three values represent the amount of rotation of the head-mounted display about the x y and z-axes. In other words, by an analysis of these angles, the orientation of the head set and hence a subject's head can be determined at any point of time. This can be held to be analogous to the approximate direction of gaze of the subject at any moment in time. Since the field of view of the head set is also known, which for this particular head set is 105°, then the precise field of view of the subject can also be recreated at any instant during their journey. The analysis of the varying field of view along a route is covered in the previous chapter, Chapter 6.

The primary question in this section of the chapter is to what extent are such head movements indicative of the actual direction of gaze or eye movement of a subject. In an important paper on predictable eye-head coordination during driving, Land (Land 1992) describes an experiment that he conducted upon subjects in a simulated driving environment. Whilst driving he measured both eye movements and head movements and found a high degree of congruity between the two.

Classical eye movement research typically involves the head being immobilized in some manner, such that it is only the movements of the eyes that are captured. Rarely have both head and eye movements been analyzed concurrently. The remarkable semblance between the head and eye movements found by Land, led him to conclude that both actions arose from a single 'direction of gaze' command. Other work in the eye movement field suggests that we rarely move our eyes more than 15° within their sockets[4] and that movement, outside this range, is instead accounted for by movement of the head. Based upon Land's work and in the absence of further research to the contrary, it could be reasonably suggested that the head movements of the subjects captured in the head set *are* indicative of the actual direction of gaze, given a small amount of error correction[5].

The first method of analysis presented in figure 7.19 overleaf analysed *all* head movements throughout a subject's journey. This data is represented by an arrow on plan, indicating the approximate direction of gaze of a subject. The locus of the direction of gaze is also indicated by a dotted line on plan.

This method of representation was felt to be less than satisfactory. This was because of the fact that although this method of visualising the data presented an accurate representation of the continuous head movement of a subject whilst navigating a virtual world, it was not particularly informative. The way in which Division's Divisor headset is configured, means that a subject navigates by looking in the direction in which they wish to travel and then using the 3d mouse to start moving. In this manner, whilst moving, the movement of the head and direction of gaze is tightly bound to the subject's method

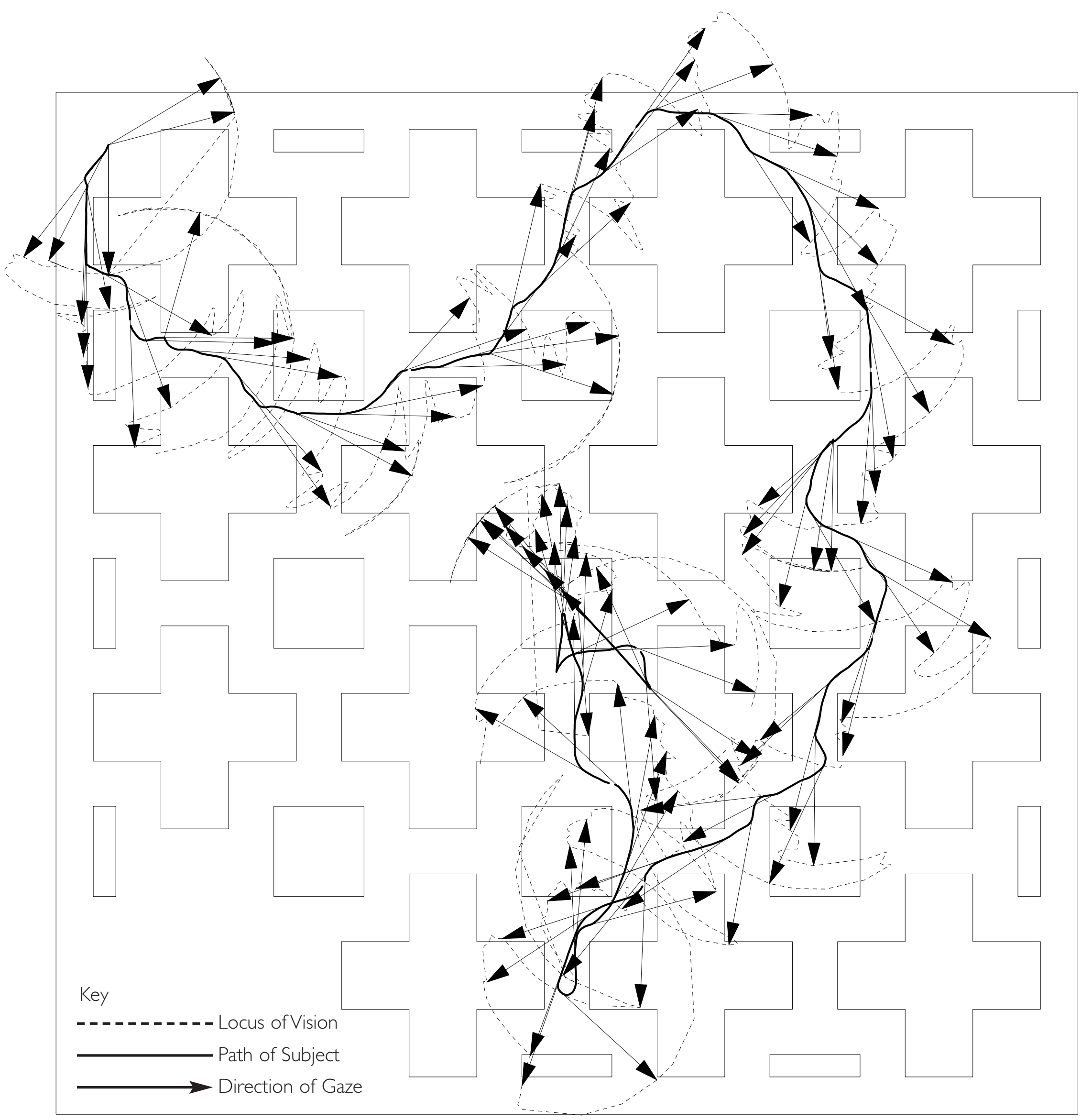


Figure 7.19 Path of a Subject through World A, showing Path, Direction of Gaze Arrows and Continuous Locus of Vision

of navigation. It was possible to reconfigure this arrangement, for example to allow a subject to move in the direction that they were pointing (with the 3d mouse). However, if the equipment were configured in this way, it would have been possible to move in one direction whilst looking in a completely different direction, even backwards. Trials conducted that experimented with severing the link between head orientation and direction of movement appeared to result in a less intuitive and harder to use interface. It was decided to continue to use the default configuration.

Instead of re-configuring the hardware a second method of analysis was developed which concentrated purely on the head movements whilst the subject was *stationary*. Whilst a subject is motionless within the environment their head movements represent their direction of gaze as they are looking around an environment. At these instances in time, a subject is not using their direction of gaze to navigate but to survey their environment.

It was decided to develop a method of graphical representation based upon this subset (only their head movements whilst paused) of the data. This new method, therefore, effectively combined both the pause points and direction of gaze data to produce a single unified representation. In this manner it is not only possible to determine where in an environment a person was pausing, but to discover in which direction they were looking whilst stationary. If, as it appears, subjects seem to be stopping at or in the vicinity of junctions, i.e. locations where a route choice decision needed to be made, then the ability to be able to reproduce and represent their head movements whilst making navigational decisions, might afford clues to this decision making process. The question can then be asked where are subjects looking in an environment in order to inform their decision-making?

An example of combined pause point and direction of gaze analysis is shown in figure 7.20 opposite. This figure opposite represents the path of a single individual navigating through World F.

The subject starts their journey in the top rightmost corner (on plan). As the subject enters the world, they initially remain motionless, turning to survey the new environment. They begin facing towards the world, turn around to look behind them (where they see the world boundary) and turn back through 180° again, before starting to move off.

The subject successfully negotiates two junctions before reaching a T-Junction. Here they are unsure whether to turn to their left or to their right. They pause to look in both directions. They elect to take the right path and continue their journey. Without hesitation they make a left-hand turn and rapidly reach a crossroads. Here they pause once more, looking to their left and right, before making the decision to move straight on. Continuing in the same direction, they walk past junctions on their left and right, before reaching another crossroads. Here they also pause to look around before deciding to move straight on as before. They finally reach the boundary of the world. This next part of their journey is not shown.

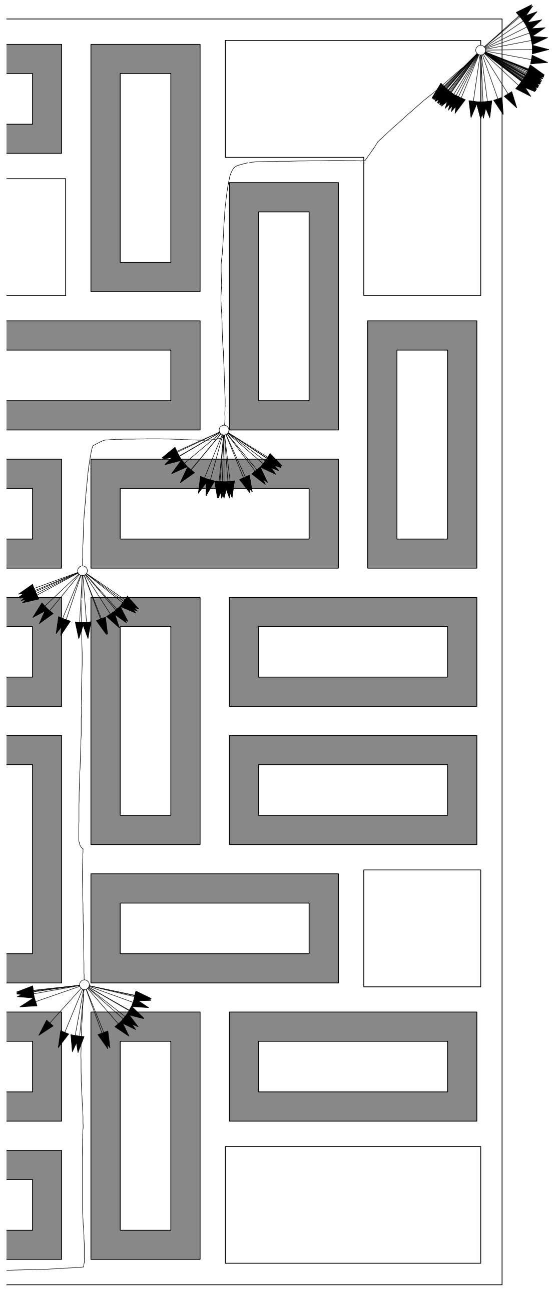


Figure 7.20 Path of an Individual in World F Illustrating their Pause Points and Direction of Gaze Arrows

The example of World C in figure 7.21 shows a person entering the world at the mid-left side. As in the previous example, they start by looking around. They do not pause again until they reach the main diagonal route to the monument. They pause a couple of times before reaching the monument. They pause just before the monument, where they stop, look at it and look around. On attempting to return to their starting position, they pause a couple more times, but fail to retrace their steps exactly.

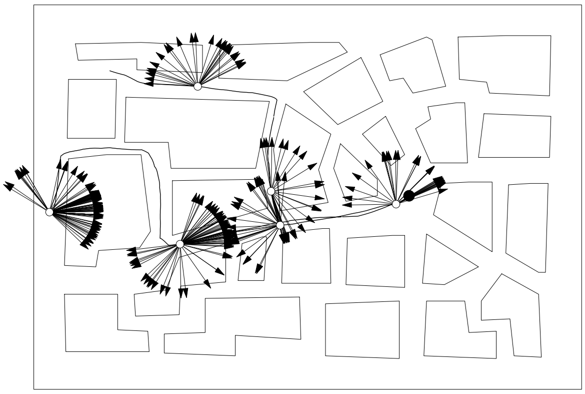


Figure 7.21 Path of Subject in World C

In World D opposite, the movement trace of another person can be seen. The positions where they pause and stop to look around are clearly discernible. This form of representation also contains an indication of time. The number of arrows radiating from a pause point is indicative of the amount of time that they are motionless. A pause point with only a couple of arrows radiating from it will represent a briefer pause than another location with a thick forest of arrows radiating from it. Another form of behaviour that is encapsulated in this form of representation can be clearly seen in figure 7.22 opposite.

Figure 7.22 Path of Subject in World D

Compare the upper-left pause point on plan (the end point of the journey) to the point on the far-left side (the start point of the journey). The radial distribution of the arrows represents the speed at which the person was turning around. If a subject spins around rapidly, the arrows are spaced far apart, such as the last pause point in the journey. If the same person is turning around very slowly that arrows will be quite densely packed. In summary, the number and spacing of the arrows radiating from a pause point can be interpreted as the relative duration of pause points and the speed that a subject turns around.

Conclusion

This chapter set out to examine a selection of smaller-scale actions that may take place during a journey. In particular, it considered locations in an environment where subjects pause for significant periods of time. Of all the methods of combined analysis and visualisation presented in this chapter, the final technique of illustrating pause points combined with approximate direction of gaze data appears to be a most successful way of representing the log file data and of capturing such small-scale actions. It is strongly suggested that where the subjects look whilst stationary is important. If this is true, then conversely what is available *to be seen* at any location must also be important. This leads to the suggestion that an attempt should be made to correlate movement data to both spatial and visual data. The type of data that most readily lends itself to such analysis is isovist data. Earlier in this chapter, it was conjectured that people appeared to be pausing in specific types of spatial location (junctions and centres of spaces). Therefore, the following chapter will begin to investigate whether there is a method of *characterising* where people are pausing in the environment in terms of that environment's visual, isovist properties. In the same way that isovist attributes can be calculated along a route generating a 'route vision profile' (Chapter 6), it is proposed to investigate the isovist characteristics of individual pause points.

Key Points

- Conclusion – People appear to be pausing at locations where route choice decisions need to be made.
- The k-means cluster algorithm can be effectively used to identify groups or clusters of pause points. However, the technique could be refined to include spatial information (such as mutual visibility between points), rendering it more useful for this task.
- A comparison of total journey time or distance travelled to stopping patterns may reveal individual characteristics of journeys.
- The combination of direction of gaze and pause point analysis appears to be the most useful method of combining the data and information available in a graphical form.
- There are possible differences between patterns of movement at the level of the building and at the urban environment level. These differences may be discerned through the duration of pause points.
- There is a possible correlation between the speed of movement and the duration of pause points. The faster a person moves, the less time they are likely to spend stationary.
- It is also possible that people pause in different types of locations in building and urban systems. In an urban environment, people appear to be pausing in proximity to road junctions. Any analogous behaviour is hard to discern at the level at the building.

Notes

1 This application was written in the C programming language.

2 Since a subject's position was measured ten times every second, in order to convert from the number of points sampled (see table 7.2) into the number of seconds spent stationary it is necessary to divide the number of points by a factor of 10.

3 Additional information exists on this sub-sample of five subjects, which might suggest reasons for the differences in their behaviour compared to the rest of the sample. By collating personal data provided by the subjects in questionnaires, it is possible to provide further information about the five subjects identified on the scattergram. These five subjects are all male. They have a slightly lower average age than the sample as a whole (28 years compared to 33 years) and an unusually high proportion of them were left-handed (three of these five subjects were left-handed).

4 Source is email correspondence with Dr. Charles Frederick Neveu, NASA Ames Research Center. Although John Stracham claims, again in email correspondence, that 7°[eye movement] is rare without head movement greater than 12°, citing the HMD handbook.

5 In conversations with Dr Graham at the Institute of Neurology, University of London, it was suggested that head movements captured by the headset used in these experiments were probably an accurate estimate of direction of gaze with an error factor of 10-20%.

Chapter Eight:
Isovist Characteristics of Stopping Behaviour

Abstract

This chapter explores a method for analysing the spatial properties of environments using techniques of isovist generation. This is performed by filling all navigable space with an array of points, each one considered to be a viewpoint from which an isovist is subsequently generated. The characteristics or attributes of all of the isovists so generated are calculated and stored. The resultant 'set' of isovist attributes is held, in statistical terms, to be a 'population'. Then, the pause point locations for each of the worlds are used as viewpoints from which a second series of isovists are computed. Again, the attributes of these isovists are calculated and recorded and in statistical terms these are held to be a 'sample' of the wider 'population'. Using a couple of statistical tests, the z-test and the central limit theorem, it is possible to compare a sample of isovists to its populations and determine how likely it is that the sample was drawn at random from that population. The results of this analysis give a more detailed and precise picture of the types of location where people are pausing in terms of the environment's specific isovist characteristics. The results of these statistical tests seem to suggest that people are not pausing randomly in the world, rather they are pausing in locations that offer maximum visual information.

Measures for Isovist Arrays

The question that emerged from the previous chapter is whether an analysis of the visual characteristics of an environment can lead to a more accurate description of a subject's stopping patterns. In Chapter 7, any patterns observed in the locations of pauses were judged purely 'by eye'. It was clear that a more sophisticated method for analysing pause point data was required. In the next section of this chapter, the results of isovist analyses of all of the seven test environments are presented. Each of these worlds was analysed using the computer application 'OmniVista'[1]. Firstly, the overall technique and methodology is explained, then the results of each world are discussed in detail. OmniVista calculates two dimensional, planar isovists, parallel to the ground plane, identical to Benedikt's original methods of isovist calculation. After importing the building plan or urban footprint-data for a world, a grid of points can be generated throughout the environment, filling all navigable space. In the following seven examples the horizontal and vertical spacing of the grid points has been set to four metres[2]. Each one of these grid points is then used as a viewpoint from which a single isovist is generated. This approach results in some of the larger worlds containing thousands of isovist viewpoints. As each individual isovist is generated, certain isovist attributes are calculated and stored. The geometric properties calculated for each isovist location are listed overleaf and measures that were used by Benedikt in his paper (Benedikt 1979) are marked with an asterisk. A brief explanation of how each measure is calculated is included in this section of the thesis.

1. Area*
2. Perimeter
3. Area/Perimeter
4. Circularity*
5. Dispersion
6. Dispersion (Absolute)
7. Drift
8. Maximum Radial Length
9. Mean Radial Length
10. Minimum Radial Length
11. Standard Deviation of Radials
12. Variance of Radials
13. Skewness of Radials.

Area is simply the area of the isovist polygon generated, namely the sum total of all visible points (on a horizontal plane). The unit for area is square metres. Perimeter, as used in this thesis, is not identical to Benedikt's measure of perimeter. Benedikt makes a distinction between two perimeter measures, real-surface perimeter and occlusivity (the sum of the length of all occluding radials). Perimeter, as used in OmniVista, is simply the perimeter of the polygon representing the isovist. The connection between this measure and Benedikt's two measures is that perimeter in OmniVista is the sum of Benedikt's measures of perimeter and isovist occlusivity. Below is the equation used by OmniVista to calculate perimeter.

$$P = \sum_{n=1}^{n=m} \sqrt{\left(\left(p_n^x - p_{n-1}^x\right)^2 + \left(p_n^y - p_{n-1}^y\right)^2\right)}$$

Equation 8.1 Formula for Calculating the Perimeter of an Isovist

Area/Perimeter is the area to perimeter ratio. The most efficient area to perimeter ratio is produced by a perfect circle. As a circle is deformed and becomes more 'spiky', the perimeter of the shape increases at a greater rate than its area. As a consequence of this deformation, the area/perimeter ratio decreases. The area to perimeter ratio, therefore, can be regarded as a good measure of how 'spiky' or conversely how 'rounded' is an isovist. It should be noted that in order to compare isovists of different environments this measure should be normalized for the size of the world. The unit for Area/Perimeter is metres.

$$Area\ perimeter\ ratio = \left(\frac{A}{P}\right)$$

Equation 8.2 Formula for Calculating the Area Perimeter Ratio of an Isovist

Circularity is a measure from Benedikt's paper. Circularity is not only a measure of how well a space approximates a circle, but is also a measure of the viewpoint's position within that space. For this reason, circularity is not only a measure of the shape of a space but also of the centrality of the viewpoint relative to its isovist. It is determined by calculating the area of a perfect circle whose radius is set to the mean radial length of the isovist and then dividing this by the area of the isovist.

$$Circularity = \left(\frac{\pi |\bar{r}|^2}{Area}\right)$$

Equation 8.3 Formula for Calculating the Circularity of an Isovist

Dispersion (a new measure in OmniVista) is the difference between the values of the mean and the standard deviation of the isovist's radial lengths. This measure can take either a positive or negative value, whereas the measure 'Absolute Dispersion' indicates purely the magnitude of the difference between the two values, irrespective of its sign.

$$Dispersion = (mean\ radial\ length) - (standard\ deviation\ of\ radials)$$

Equation 8.4 Formula for Calculating the Dispersion of an Isovist

Drift (a new measure in OmniVista) is an exceedingly interesting measure. It is the distance in metres between the location from which the isovist is generated and its 'centre of gravity'. The centre of gravity of an isovist is calculated as if the isovist were a polygonal lamina[3] of negligible but uniform thickness, as calculated in physics. This measure can only take positive values. Drift will tend towards a minimum value at the centres of spaces and along the centre-lines of roads. For this reason, similarities can be seen between areas of minimum drift and the axial breakup of spaces.

$$Drift = \sqrt{\left((d_y - c_y)^2 + (d_x - c_x)^2\right)}$$

Equation 8.5 Formula for Calculating the Drift of an Isovist

Maximum, mean and minimum radial length are calculated by measuring the lengths of isovist radials at specified intervals (for example every one-degree). These three attributes are generated by calculating the maximum length of any radial (or the longest line of sight), the mean length of all the radials (another measure of 'spikiness') and the minimum length of the radials (or the distance from the isovist viewpoint to the closest built edge). Figure 8.1 overleaf illustrates the relationship between an isovist's radial lengths and the isovist polygon. Mean radial length appears to be a good indicator of junctions in urban systems.

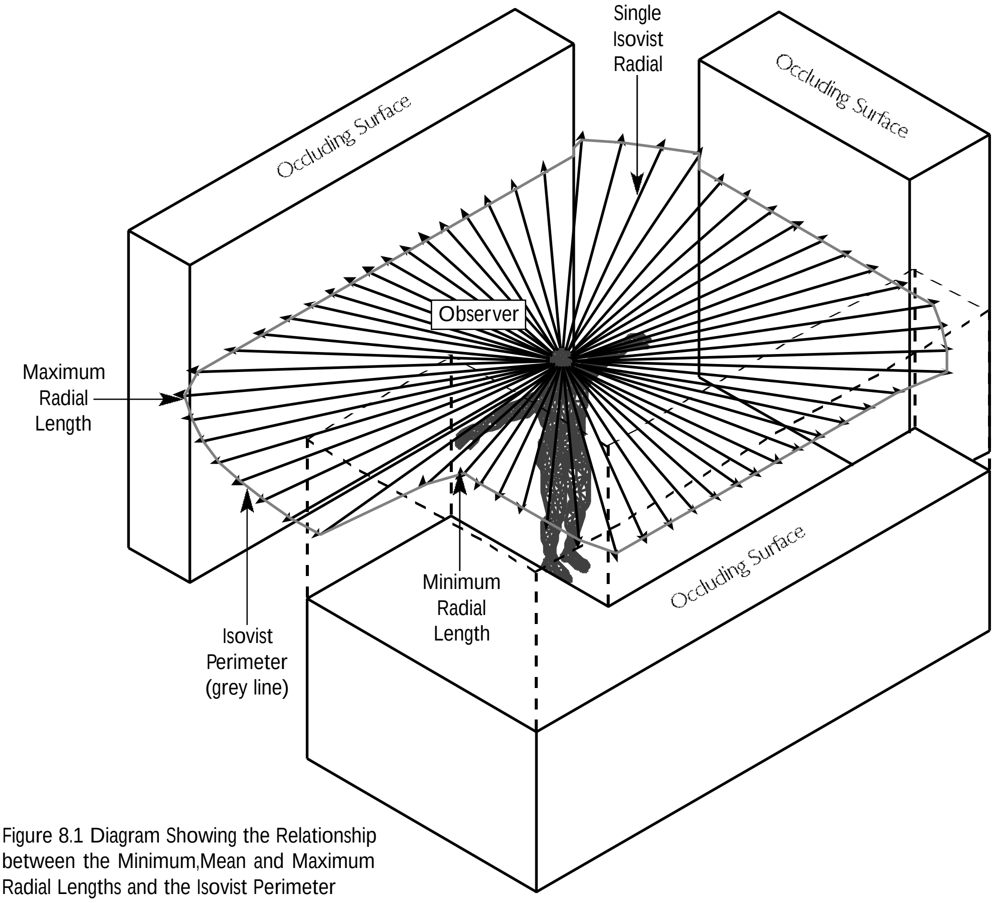


Figure 8.1 Diagram Showing the Relationship between the Minimum,Mean and Maximum Radial Lengths and the Isovist Perimeter

$$Maximum\ radial\ length = \left\lceil \sqrt{\left(\left(p_n^x\right)^2 + \left(p_n^y\right)^2\right)}_{n-1}^{n=m} \right\rceil$$

$$Average\ radial\ length = \left(\frac{1}{m}\right)\sum_{n=1}^{n=m} r$$

$$Minimum\ radial\ length = \left\lfloor \sqrt{\left(\left(p_n^x\right)^2 + \left(p_n^y\right)^2\right)}_{n-1}^{n=m} \right\rfloor$$

Equation 8.6 Formula for Calculating the Maximum, Average and Mean Radial Lengths of an Isovist

Standard deviation, variance and skewness of radials are also a family of measures based upon the distribution of the radial lengths of an isovist. Standard deviation is calculated by taking the sum of the differences between each radial length and the mean of the radial lengths of the isovist and then dividing this sum by the number of isovist radials. Variance can be calculated by multiplying the standard deviation by itself. Variance can also be termed the second moment of the isovist and is a measure used by Benedikt. Skewness is the third moment of the radials, calculated by summing the cube of the differences between each radial length and the mean of the radial lengths and then dividing this total by the number of isovist radials. Skewness is also a measure used by Benedikt, who suggests that it is a good indicator of asymmetry of the perimeter of an isovist polygon.

$$Second\ moment\ (\sigma) = \left(\frac{1}{m}\right)\sum_{n=1}^{n=m} r^2$$

$$Third\ moment\ \left(m^3\right) = \left(\frac{1}{m}\right)\sum_{n=1}^{n=m} r_n^3$$

$$Variance = \sqrt{\sigma}$$

Equation 8.7 Formula for Calculating the Standard Deviation, Third Moment and Variance of the Radial Lengths of an Isovist

After calculating all of the above measures, OmniVista stores them and produces a coloured visualisation of the data. Each viewpoint (from which an isovist was generated) is represented by a point on plan. The colour of the point is assigned using the value of each measure. A rainbow spectrum is employed in which red denotes the maximum value and blue represents the minimum value of a measure. The colours orange, yellow and green are assigned respectively for the intermediate values. Each distinct measure of the geometric property of an array of isovists can therefore be illustrated by its own diagram.

When the above attributes have been calculated for each isovist, the relationship between every isovist viewpoint and every other isovist viewpoint may be examined and a graph representation of intervisibility or the 'visibility graph' is constructed. There are two possible types of connection, the first describes a condition of mutual visibility between the viewpoints themselves (i.e. two people standing at each isovist's viewpoint can see each other). The second type of connection is formed if the isovists polygons overlap, but neither viewpoint is located inside the isovist of the second (since this would be case one). In this scenario any two people standing at these viewpoints would not be able to see one another directly but both could see a third person standing in the region represented by the union of the two isovists. These relations have been termed first order and second order relationships by Turner et al. (Turner, Doxa et al. 2001). The calculations performed by OmniVista are based upon a first order visibility relationship.

Once the visibility graph has been generated, this set of relationships can be used to develop a set of 'syntactic' measures in a similar manner to those used earlier in the thesis (see Chapter 1 and Chapter 4). In essence, the relationship between every viewpoint and every other viewpoint in the system is calculated and the distance (in graph terminology) is calculated between all pairs of points. The isovist viewpoints are then represented as nodes in the graph while the relationship of mutual visibility is represented as links between these nodes. The values calculated are shown below.

- Connectivity
- Mean Depth
- Radius 3 Depth
- Total Depth

Connectivity, is simply a measure of how many other viewpoints are visible from a viewpoint. Each isovist will have its own connectivity value, which will be an integer number (since in this particular calculation two isovists are either connected or not, there are no gradations of connection[4]). It is clear that there will be a strong relationship between an isovist's area and its visibility graph connectivity. If the distribution of generating locations is uniform then connectivity is a good approximation to isovist area.

The total depth of an isovist array is the sum of the distances of an isovist viewpoint from all other isovist locations in the array (distance in graph terms). Mean depth, however is the *average* distance from each isovist location to every other isovist location (in other words total depth divided by the number of isovists in the graph, n, not including itself, i.e. n-1). This value is a real number. Radius 3 depth is the sum of the distance of all points that are three or less steps (in the graph) from the isovist viewpoint.

$$Mean\ depth = \frac{1}{n}\left(\sum_{n=0}^{n=k} d_n\right)$$

Equation 8.8 Formula for Calculating the Mean Depth of an Isovist

All these Space Syntax measures can also be visualised by representing each isovist location as a point on plan and determining the colour of the point using its syntactic value. Red represents the highest and blue the lowest values. In terms of connectivity, the red values are those locations that are highly visible from many other locations and equally those that command a view that includes the viewpoints of many other isovists. When visualising total depth and mean depth, the isovist locations at the red end of the spectrum represent those isovist locations that are highly integrated or a shorter distance (in graph terms) from all other isovist locations in the system. (In this case red = low depth or high integration).

The relationship between geometric and syntactic measures of isovists

Before presenting the isovist analysis of the seven worlds, it should be noted that there are strong relationships between some geometric measures of isovists and their syntactic values. In the previous section of this chapter, it was suggested that that isovist connectivity was an extremely good approximation to isovist area. The relationship between the two measures can be demonstrated using the isovist attribute correlation matrix[5] in table 8.1 below. The r-squared value representing the relationship between isovist area and connectivity is 0.998.

As well as area, connectivity also correlates well with a number of other geometric values. The correlation matrix shows that the relationship between connectivity and the maximum radial length of an isovist has an r-squared value of 0.733. Maximum radial length is a measure of the longest available line of sight from an isovist's viewpoint. The longer the line of sight from a viewpoint, the more likely it is to

	Area	Perimeter	Area/Perimeter	Min. Radial Length	Max. Radial Length	Mean Radial Length	Circularity	Standard Deviation	Third Moment	Drift	Dispersion	Total Depth	Mean Depth	Connectivity	Radius 3 Total Depth	Mean Depth Radius 3	Variance
Area	1.000	0.796	0.699	0.197	0.733	0.799	0.154	0.937	0.711	0.268	0.320	0.587	0.587	0.998	0.285	0.006	0.925
Perimeter	0.796	1.000	0.300	0.192	0.672	0.748	0.070	0.740	0.501	0.213	0.176	0.707	0.707	0.805	0.428	0.036	0.691
Area/Perimeter	0.699	0.300	1.000	0.135	0.449	0.585	0.147	0.702	0.438	0.163	0.250	0.342	0.342	0.691	0.163	0.002	0.638
Min.Radial Length	0.197	0.192	0.135	1.000	0.104	0.401	0.114	0.094	0.049	0.074	0.057	0.147	0.147	0.193	0.082	0.027	0.072
Max.Radial Length	0.733	0.672	0.449	0.104	1.000	0.483	0.300	0.821	0.780	0.264	0.487	0.460	0.460	0.733	0.263	0.002	0.796
Mean Radial Length	0.799	0.748	0.585	0.401	0.483	1.000	0.001	0.658	0.310	0.091	0.031	0.658	0.658	0.801	0.401	0.023	0.557
Circularity	0.154	0.070	0.147	0.114	0.300	0.001	1.000	0.329	0.359	0.241	0.870	0.059	0.059	0.154	0.029	0.022	0.339
Standard Deviation	0.937	0.740	0.702	0.094	0.821	0.658	0.329	1.000	0.759	0.332	0.516	0.596	0.596	0.937	0.326	0.000	0.958
Third Moment	0.711	0.501	0.438	0.049	0.780	0.310	0.359	0.759	1.000	0.354	0.645	0.276	0.276	0.707	0.097	0.000	0.876
Drift	0.268	0.213	0.163	0.074	0.264	0.091	0.241	0.332	0.354	1.000	0.372	0.158	0.158	0.276	0.073	0.000	0.378
Dispersion	0.320	0.176	0.250	0.057	0.487	0.031	0.870	0.516	0.645	0.372	1.000	0.112	0.112	0.319	0.044	0.023	0.579
Total Depth	0.587	0.707	0.342	0.147	0.460	0.658	0.059	0.596	0.276	0.158	0.112	1.000	1.000	0.604	0.839	0.017	0.482
Mean Depth	0.587	0.707	0.342	0.147	0.460	0.658	0.059	0.596	0.276	0.158	0.112	1.000	1.000	0.604	0.839	0.016	0.482
Connectivity	0.998	0.805	0.691	0.193	0.733	0.801	0.154	0.937	0.707	0.276	0.319	0.604	0.604	1.000	0.298	0.006	0.924
Radius 3 Total Depth	0.285	0.428	0.163	0.082	0.263	0.401	0.029	0.326	0.097	0.073	0.044	0.839	0.839	0.298	1.000	0.005	0.218
Mean Depth Radius 3	0.006	0.036	0.002	0.027	0.002	0.023	0.022	0.000	0.000	0.000	0.023	0.017	0.016	0.006	0.005	1.000	0.000
Variance	0.925	0.691	0.638	0.072	0.796	0.557	0.339	0.958	0.876	0.378	0.579	0.482	0.482	0.924	0.218	0.000	1.000

Table 8.1 Correlation Matrix for Isovist Attributes

connect with other isovist viewpoints and the good correlation between connectivity and maximum radial length demonstrates this.

There is an even better correlation between connectivity and mean radial length, with an r-squared value of 0.801. Mean radial length is a good indicator of the location of road junctions. At junctions, the isovists that are generated are particularly spiky, with 'fingers' of visibility that stretch down every street leading from that junction. The 'spikier' the isovist, the more likely it is to be well connected, for exactly the same reason that a long line of sight will be well connected. As well as correlating highly with connectivity, mean radial length also has a significant correlation with mean depth and total depth. Although this relationship is not as strong as the relationship between the mean radial length of the isovist radials and isovist connectivity, it is still a good correlation. This suggests that when analysing urban areas using visibility graphs, junctions are more likely to represent integrated rather than segregated locations. The r-squared for this relationship is 0.657.

The standard deviation of radial lengths is another measure of the spikiness of an isovist and can result in higher than average values at locations such as road junctions in urban areas. Although the relationship between radial length standard deviation and mean depth is good, (r-squared of 0.596) it is not as good as the relationship between mean radial length and mean depth.

Maximum radial length correlates well with connectivity, so it is no surprise that it should also correlate fairly well with mean depth and total depth. This correlation is not as good as the correlation with connectivity (an r-squared of 0.459 compared to 0.733). The reason for this is that if a particularly long line of sight radiates from an isovist viewpoint, then it is *probable* that this isovist will connect with a number of other isovist viewpoints. If an isovist is well connected it is likely to be integrated too, but this is not a surety, which explains why the relationship between maximum radial length and mean depth is not as good as the relationship between maximum radial length and connectivity.

Another strong relationship that exists between mean depth and one of the geometric measures of an isovist, but one that essentially owes this correlation to connectivity, is the relationship between area and integration. The r-squared correlation coefficient for the relationship between area and integration is 0.587. Because area is such a good approximation to connectivity, then the relationship between connectivity and mean depth is consequently a significant one. The r-squared of the correlation between connectivity and mean depth is 0.603.

The relationship between geometric measures of isovists and syntactic measures of isovists, as demonstrated above, is highly significant. The geometric properties of isovist are measures of the *single isovist* in which an observer stands. These are local properties and can be instantly apprehended by someone standing in the space. A person standing in a landscape can look around and immediately perceive the size of the space they are occupying, the shape of the space, whether or not it is an open space evenly distributed about their standing point or they are situated to one edge of it or perhaps it is a particularly 'spiky' space, allowing glimpses of other spaces past occluding surfaces. All of this information can be judged by a person who is visually surveying their environment. The syntactic measures, in contrast with geometric measures are not properties of an individual isovist considered in isolation but are properties of that isovist's relation to all other isovists in the system. The syntax measures of the isovists refer to the *overall structure* of the world, be it a building or an urban area. The fact that there is a strong correlation between certain geometric measures of isovists and syntactic measures implies the potential to make global inferences from purely local information. This means that a person can pause in an environment and make a judgement about their position within *the whole system* based on visual information of the space that they are occupying. It also implies that when wayfinding, a subject may be strategic about the direction they choose to take (whether or not this is a conscious decision). This conjecture is supported in the next section of this chapter where the geometric and syntactic properties of isovists at pause point locations are compared to the distribution of isovist measures throughout the world.

Isovist Analysis of Worlds

Each of the seven worlds in the following section has been analysed using the application OmniVista. The presentation of the results of the analysis is followed by a discussion of the distribution of isovist results as calculated for each measure and for each world.

Since, in the previous chapter, it was suggested that people were pausing in the vicinity of road junctions, this hunch can now be tested using isovist data. If the complete set of all possible isovists is held to be a 'population', in the statistical sense, then this population can be compared to the 'sample' of isovist properties calculated for each of the pause point locations (as described in Chapter 7). There are many statistical methods for comparing a sample (from a population) to the population itself to determine how *representative* that sample is of the whole population. The two[6] methods used in this chapter are the central limit theorem and the z-test. The z-test relies upon the population being approximately normal (either one-tailed or two-tailed) whereas the central limit theorem can be applied to a completely random population.

The central limit theorem states that for any sample population drawn from a population (which need not be normally distributed) then as long as the sample size is relatively large (n>10) then the distribution of the sample will be approximately normal. The larger the size of the sample the better the approximation. The sample size of pause points used in this section of the chapter is very large, using this definition. If the population is not normally distributed, then the sample will only ever approximate a normal distribution whose mean will be the same as the population mean. The value of z using the central limit theorem is shown below.

$$z = \frac{\bar{x} - \mu}{\sigma_{\bar{x}}}$$

Equation 8.9 Formula for Calculating z using the Central Limit Theorem

Where μ is the mean of the population, $\sigma_{\bar{x}}$ is the standard deviation and $\bar{x}$ is the mean of the sample.

The z-test is a statistical method for comparing a sample against a population to determine how *likely it is* that the sample was drawn from that particular population. The test relies on knowing the values for the mean and variance of both of the samples. The test requires stating a hypothesised mean difference, which since the hypothesis being tested here is that the sample could have been randomly drawn from the population, then the hypothesised mean difference is zero. A confidence level is also required for this test and the standard 95% confidence level has been used. Essentially, if the resultant value of z is less than a specified value (listed on a statistical look-up table), then the sample (the pause points) could have been drawn at random from the population (the isovist array). If the value of z is larger, then it implies that subjects were not pausing randomly.

In essence, the sample of isovist measures for each pause point location is compared against the population of the equivalent measure for each grid isovist location. Two values of z are calculated for each measure (one using the central theorem limit and one using the z-test). If z is less than a specified value (1.65 for a one-tailed distribution and 1.96 for a two-tailed distribution) then there is a 95% confidence that the sub-sample could have been randomly drawn from the population sample. In other words, if the value of z is less than 1.65 or 1.96, then in terms of the visual properties of the environment, subjects are pausing randomly and the visual and spatial layout of the environment has *no effect* upon their stopping behaviour. If, however, the value of z is greater than this amount, then it is unlikely that the sample of pause points was drawn randomly from the population of the grid isovist locations. The sign of z (i.e. whether it is a positive or negative number) is not important in this particular case; it is the magnitude of z that is significant. The values of z from the two statistical tests are presented as a table for each world. These tables contain the results for each measure (both geometric and syntactic) along with other statistical descriptions of the population and sample such as their means, standard deviations and variances. The results are ordered by descending, absolute values of z (from the z-test), that is to say those isovist attributes which have a greater effect upon stopping behaviour are at the top of the tables and those attributes with least effect upon stopping behaviour are sorted to the bottom of the lists. A line is drawn upon each table indicating the 1.65 and 1.96 values of z. After discussing the distribution of isovist measures for each world the results of the z-tests are presented and are discussed.

World A, The Tate Gallery

Area, Perimeter and Area/Perimeter

In World A, The location of greatest isovist area is found at the centre of the Tate Gallery, the area known as the Sackler Cupola. From this location, it is possible to see up and down the entire length of the building and through into the side-galleries. Other locations of high isovist area occur at the intersection of major visual axes. Most of the central galleries have a higher than average isovist area value and many of the side galleries have a lower than average value (unless a major axial line passes through them). The pattern of the distribution of values of isovist perimeter initially appears to reflect (with only minor differences) that of area. The light blue, diagonal lines appearing in the upper, right-most corner and crossing the main axis (just below the Sackler Cupola) are more prominent for the measure perimeter than for area. Whereas the pattern of distribution of the measure area/perimeter ratio is quite different to area and perimeter; the main visual axes have low values and the higher val-

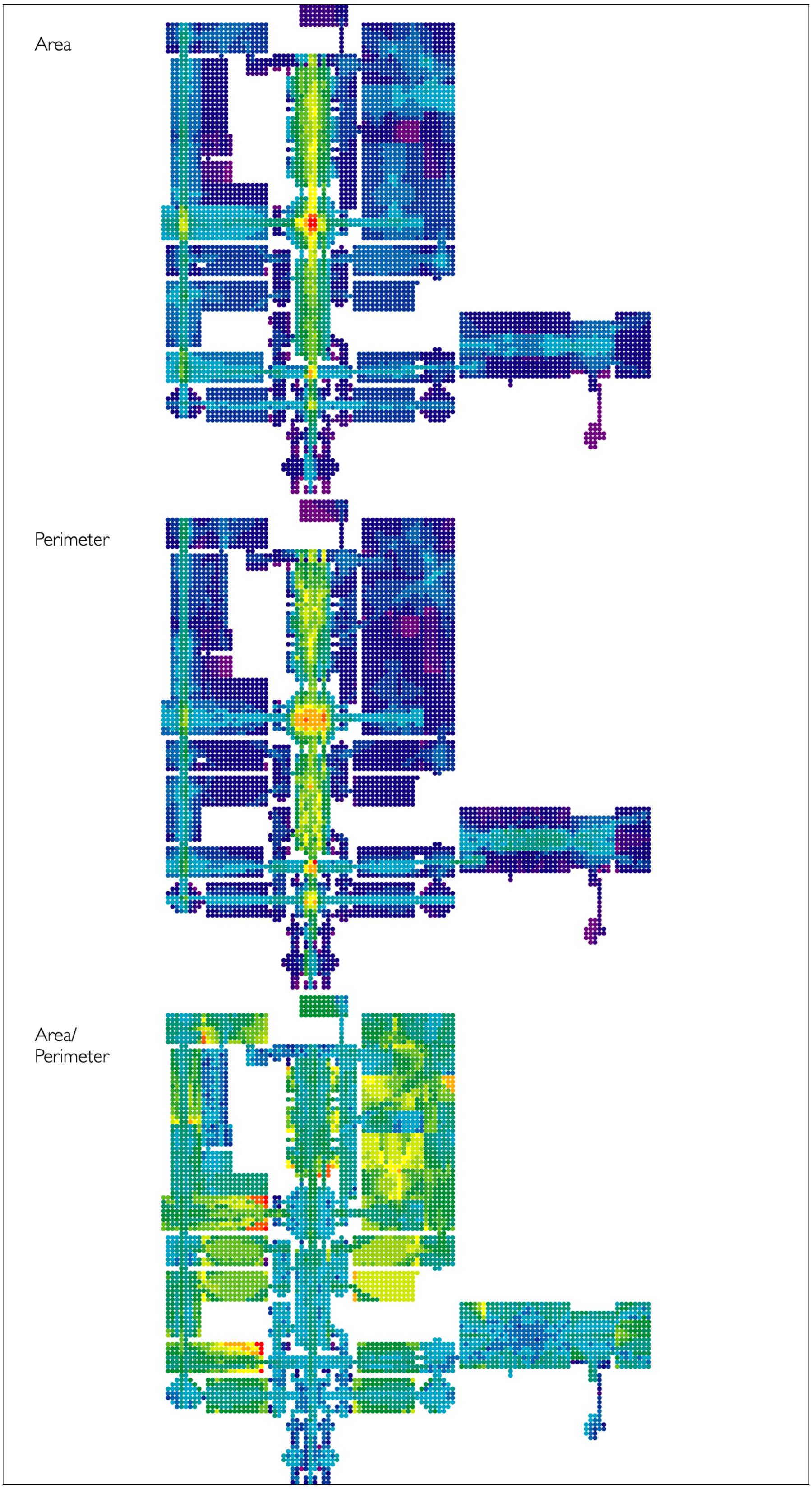


Figure 8.2 Isovist Attribute Maps for World A (Area, Perimeter & A/P)

ues are to be found in the side galleries. Since Area/perimeter is a measure of the roundness of a space, then smaller, self-contained galleries are likely to contain less 'spiky' isovists, than for example, the main axis.

Minimum,Mean and Maximum Radial Length

Minimum radial length is a measure of how close or distant a viewpoint is from an occluding surface. Therefore, the visualisation of the isovists' minimum radial lengths in the Tate Gallery emphasises the gallery's cellular design. The measure maximum radial length identifies the longest lines of sight in the building. In World A, these occur at either end of the main visual axes. Mean radial length, which (it is suggested) is a good indicator of road junctions in urban systems, appears to represent something quite different at the building level. It appears to be identifying areas of overlap between convex spaces. As junctions in urban systems are locations where route choice decisions need to be made, then this definition could be applied to these areas identified by the measure of mean radial length in the Tate Gallery.

Standard Deviation,Variance and Skewness of Radial Lengths

Standard deviation indicates the range of radial lengths for any single isovist. In World A, the areas with the greatest range of isovist radial lengths occur at the intersection points of major axes in the building, for example beneath the Sackler Cupola. In this location, extremely long lines of sight and quite short isovist radial lengths (indicating the distance from the isovist viewpoint to the nearest wall) can be found. Since the range of these values is large then the value of standard deviation will high. These locations indicate isovists that are 'spiky' in shape. Variance has the effect of dampening the lower values and highlighting the higher values so that the pattern of 'spikier' isovists is reinforced. This effect can also be seen in the measure skewness.

Circularity, Drift and Dispersion

Circularity is a measure of how closely an isovist approximates a circular disc. When applied to the Tate Gallery it emphasises the cellular or room-based spatial structure of the building. The centres of these rooms have a higher value of circularity than the edges of the rooms. The pattern of circularity is very similar to the pattern of dispersion, one being approximately the reciprocal of the other. The pattern of drift in World A is quite interesting as the values tend towards local minima at the centres of long thin spaces. These areas of minimum-drift are to be found in both cellular-rooms and long thin spaces linking them into a network of paths extremely suggestive of pedestrian movement.

Syntactic Measures

The visualisation of the values of isovist connectivity is similar to that of isovist area, a measure that it approximates. Locations of high isovist connectivity (and area) are located at strategic points along the main axis. The central galleries have relatively high levels of connectivity compared to the population as a whole. The distribution of isovist measure mean depth illustrates that the central axis is the most integrated part of the building followed by the two cross axes closest to the entrance. The axis that runs down the left-most galleries is also highly integrated. Finally, the cross axis running through the centre of the building is noticeably integrated. The galleries to the right of the central axis are more segregated that

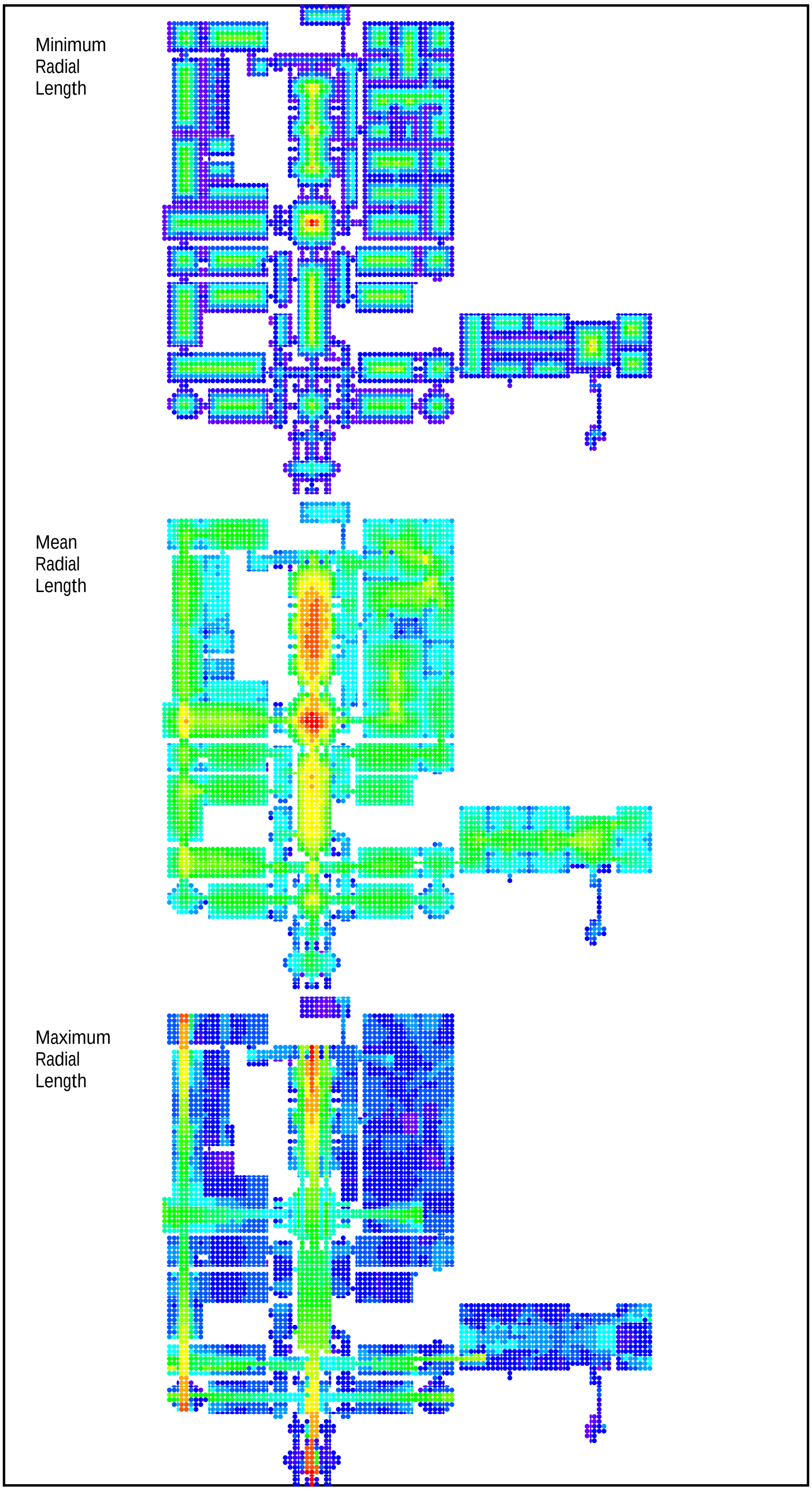


Figure 8.3 Isovist Attribute Maps for World A (Minimum,Mean & Maximum Radial Length)

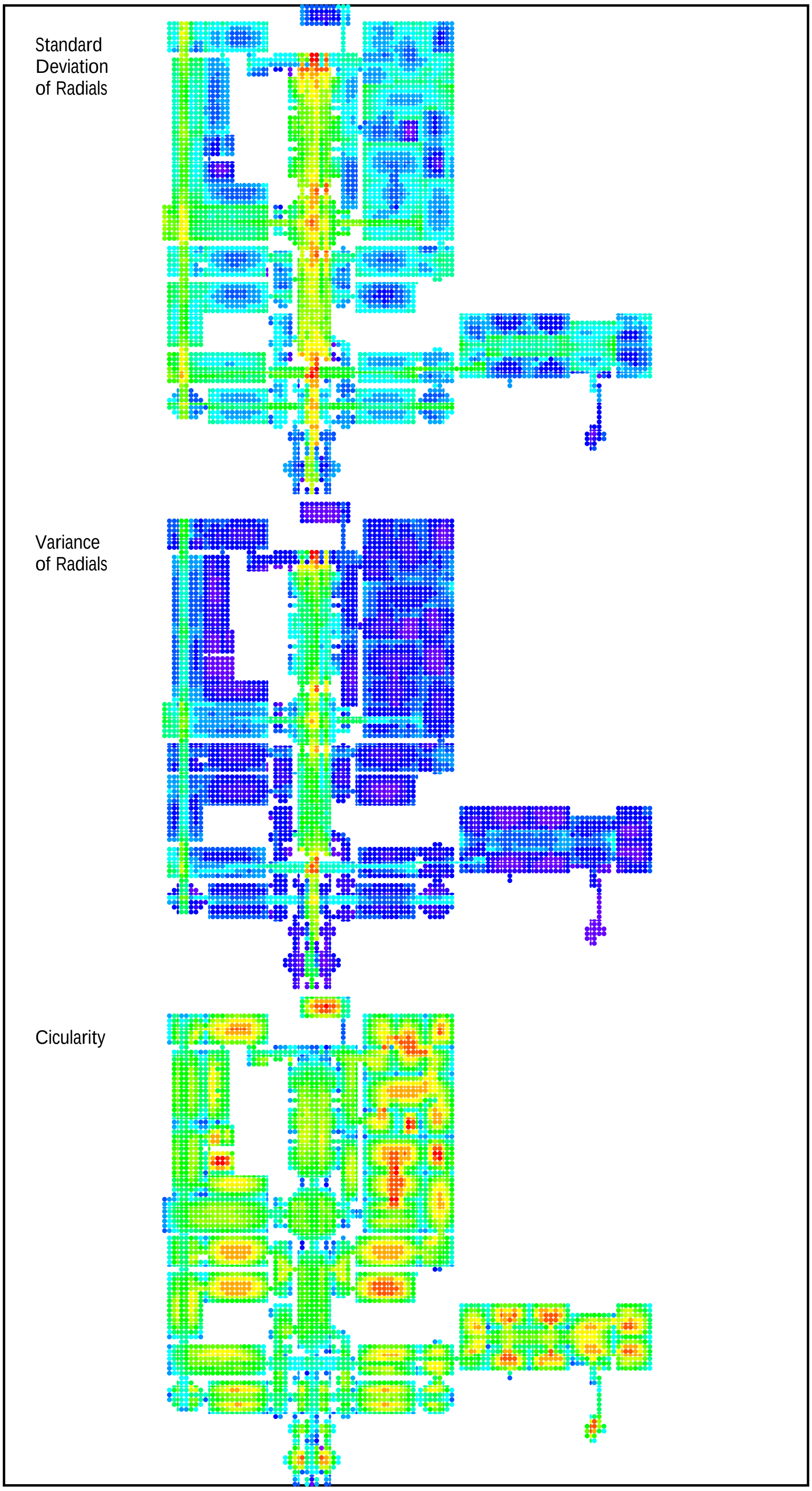


Figure 8.4 Isovist Attribute Maps for World A (Standard Deviation & Variance of Radials & Circularity)

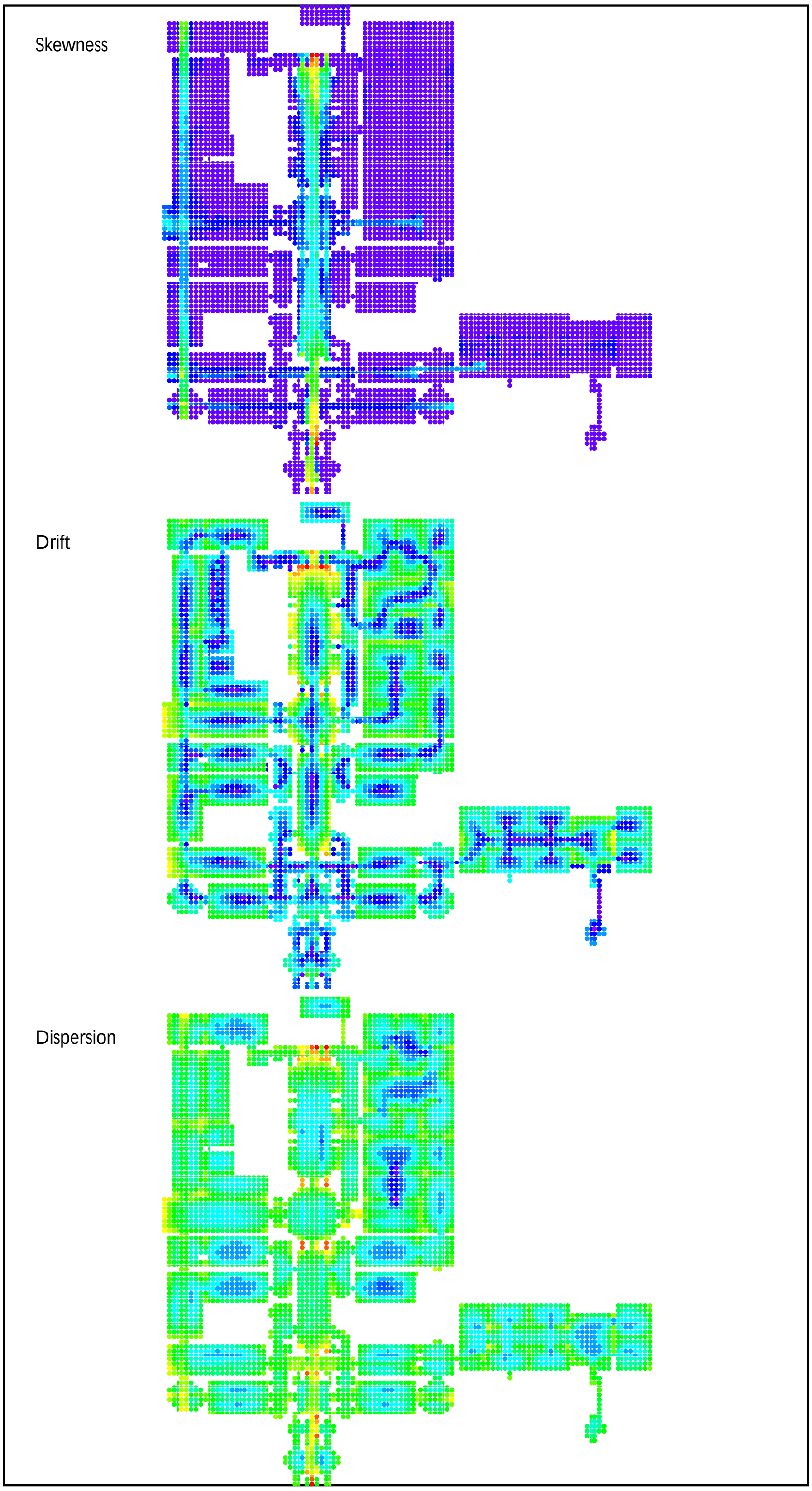


Figure 8.5 Isovist Attribute Maps for World A (Skewness of Radials,Drift & Dispersion)

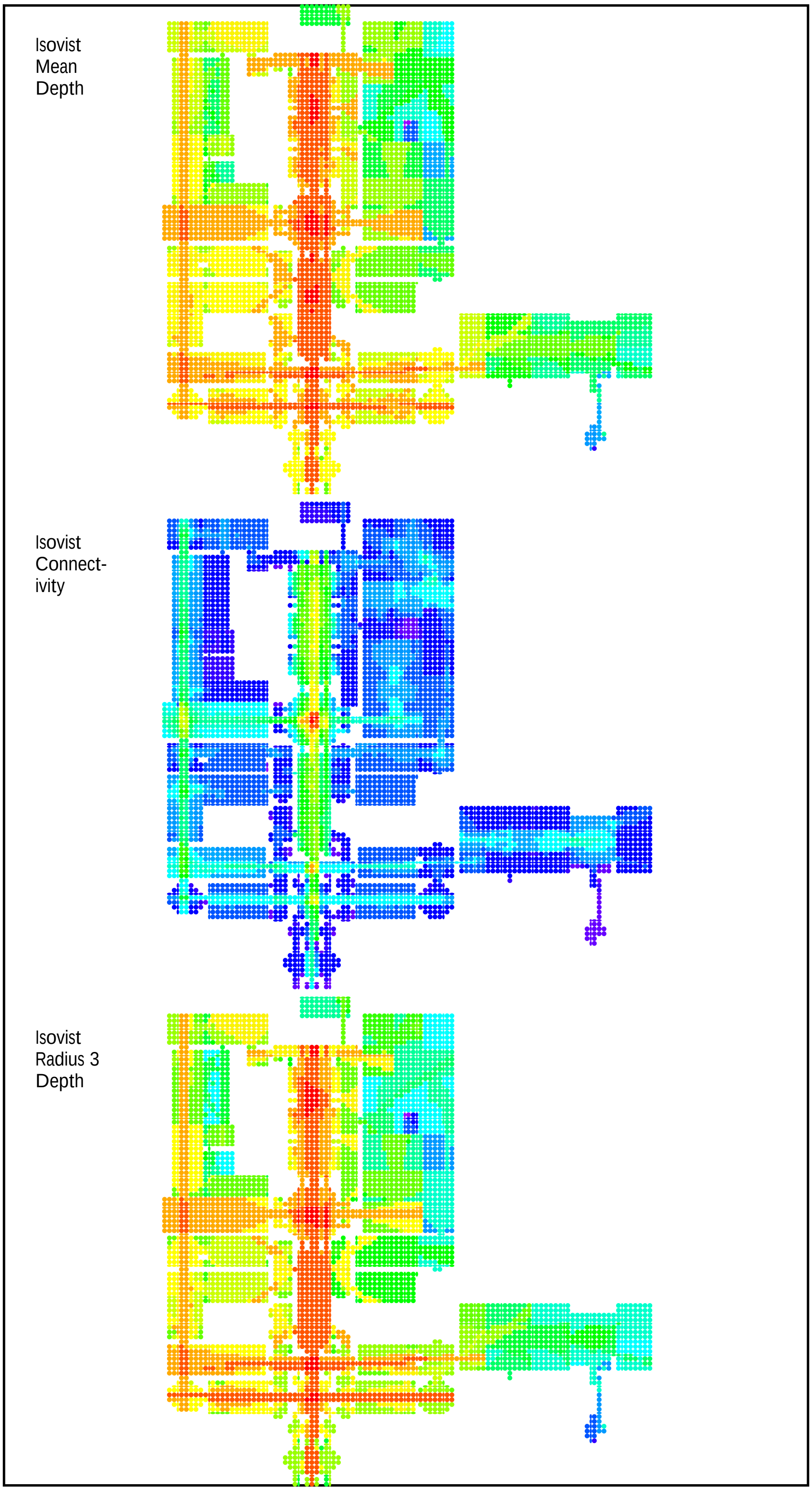


Figure 8.6 Isovist Attribute Maps for World A (Mean Depth,Connectivity & Radius 3 Depth)

those to the left. Both the 'pay-per-view' galleries (upper right) and the Clore Galleries (lower right) are quite segregated compared to the rest of the building. This method of analysis also highlights a number of diagonal lines (of integration), which cross the central axis just below the Sackler Cupola. These represent thin, penetrating lines of sight that link the central galleries to the smaller side-galleries. These lines of sight are noticeable when walking around the real Tate Gallery and are a phenomenon also found by Turner (Turner, Doxa et al. 2001) when performing similar but independent analyses.

Pause Point Sampling

The results of the two statistical tests, the z-test and the central limit theorem, are presented in table 8.3 overleaf. According to the results of the z-test there is only one measure that can be considered to have *no effect* upon people's stopping behaviour and this is circularity. However, the value of z for circularity is close to the value at which the pause points could have been selected randomly. The value of z, below which the pause points could have been random is 1.96 and the value of z for circularity is 1.97.

For the Tate Gallery, the attribute that is least likely to have been selected at random from the whole population is drift. The mean value of drift for the population is 6.86m whereas the mean of drift for the sample of pause points is 4.81m. Since drift tends to towards minimum values at the centres of spaces (both rooms and corridors) then it seems appropriate that people should be stopping in these locations. It has already been observed that the patterns of drift in the Tate Gallery bear a striking resemblance to patterns of movement (partly, of course, since subjects tended to navigate through the centres of spaces). It should therefore be no surprise that the difference between the mean value of drift for the pause points compared to the building is so great.

The table of results also indicates that people were pausing in locations with a much higher than average isovist perimeter value (651.11m compared to 457.66m) and consequently a much smaller area/perimeter value (5.17m compared to 5.85m) and locations which offered longer lines of sight (173.22m compared to 113.22m). All of these results are connected. Locations which permit the viewer long lines of sight would consequently have a larger than average perimeter and lower area to perimeter ratio. In the Tate Gallery, the parts of the building whose isovists have a high perimeter value are predominantly located at the ends of long visual axes (for example at the entrance looking through to the main galleries). The areas of greatest isovist perimeter, however, are mostly concentrated on the junctions of the major visual axes. Both of these locations appear to be ideal locations for subjects to stop. Pausing at locations with a longer than average line of sight is strategically sensible. Locations with an unusually high isovist perimeter value or at the intersection of major visual axes are locations where a route choice decision needs to be made. Pausing at such a point to scrutinise the environment would appear to be natural wayfinding behaviour. Reinforcing the above results is the fact that people are also stopping in locations with much higher than average radial standard deviation, variance and skewness. These are shown in table 8.2 below.

	Standard Deviation	Variance	Skewness
Population mean	22.19	584.28	76509.65
Pause point mean	18.29	382.35	26793.18

Table 8.2

Measure	Population mean	Sample (PP) mean	Population standard deviation	Sample (PP) standard deviation	Population variance	Sample (PP) variance	“Z” from c. l. t.	“Z” from Z-test
Drift	6.86	4.81	3.19	2.92	10.15	8.53	-10.84	11.47
Perimeter	457.66	651.11	297.67	342.51	88626.12	117313.26	10.91	-9.3
Maximum Radius Length	113.22	173.22	72.56	109.95	5265.63	12089.54	13.89	-9.06
Radial Skewness	26793.18	76509.65	46146.39	97590.77	2129892402.09	9523957768.03	18.09	-8.5
Radial Variance	382.35	584.28	298.46	426.44	89095.14	181848.03	11.36	-7.85
Area/Perimeter	5.85	5.17	1.55	1.43	2.39	2.05	-7.45	7.81
Radius 3 Total Depth	17454.95	13900.27	7301.43	7972.78	53320910.84	63565197.4	-8.18	7.32
Connectivity	161.87	212.12	99.55	117.87	9911.31	13893.44	8.48	-7.03
Area	2570.93	3357.86	1550.19	1868.6	2403541.47	3491677.56	8.52	-6.95
Radial Standard Deviation	18.29	22.19	6.92	9.6	47.95	92.23	9.47	-6.73
Mean Depth	4.24	3.84	0.9	1.01	0.82	1.02	-7.49	6.56
Total Depth	22396.12	20270.38	4765.93	5333.69	22718408.22	28448266.71	-7.49	6.55
Mean Radius	20.78	22.7	6.49	7.26	42.11	52.65	4.97	-4.35
Mean Depth Radius 3	4.58	4.4	0.69	0.68	0.47	0.46	-4.26	4.21
Dispersion	-2.49	-0.51	5.71	8.34	32.57	69.58	5.84	-3.94
Absolute Dispersion	4.98	6.28	3.74	5.51	14.01	30.31	5.83	-3.92
Minimum Radius Length	5.3	5.94	3.92	3.95	15.4	15.62	2.73	-2.64
Circularity	0.58	0.56	0.14	0.17	0.02	0.03	-2.45	1.97

Table 8.3 Tabulated Population and Sample Data from World A

Since the areas of highest radial standard deviation, variance and skewness also occur at the intersections of the major visual axes throughout the gallery, then this finding entirely supports the results for perimeter and longest line of sight.

In terms of Space Syntax measures, it also appears that people are pausing strategically. Subjects are stopping in locations with a higher than average isovist connectivity (212.12 compared to 161.87) and are pausing in locations with a lower than average mean depth (3.84 compared to 4.24). In summary, people are pausing in locations that are highly connected and highly integrated in terms of the building as a whole. They are pausing in locations where they are more likely to glean the maximum information about the configuration of the building (both local and global information). They are pausing in locations where they can see more of the building, where there are long, penetrating lines of sight and subjects are pausing at important locations such at the intersections of primary visual axes.

World B

Area, Perimeter and Area/Perimeter

The viewpoints that generate isovists of the largest area in this world are those at its corners. The boundary roads are also distinguished by containing isovists of large area. If the spaces inside the world (i.e. excluding the boundary roads) are examined, clearly the central open space (the location of the monument and the wayfinding goal) contains isovists of greater area compared to adjacent streets. This pattern is mirrored by the distribution of perimeter values. However, the pattern of isovist area/perimeter values is quite different, the areas of high area/perimeter are at the corners of the open square in the centre of the world. The shapes of these isovists are approximately square. In each of the four corners of the world there is a patch of isovists of high area/perimeter ratio, these being the convex corners of the cruciform blocks facing the boundary corners. The areas of least area/perimeter are those isovists that are particularly ‘spiky’, these are shown as dark blue or purple in the figure.

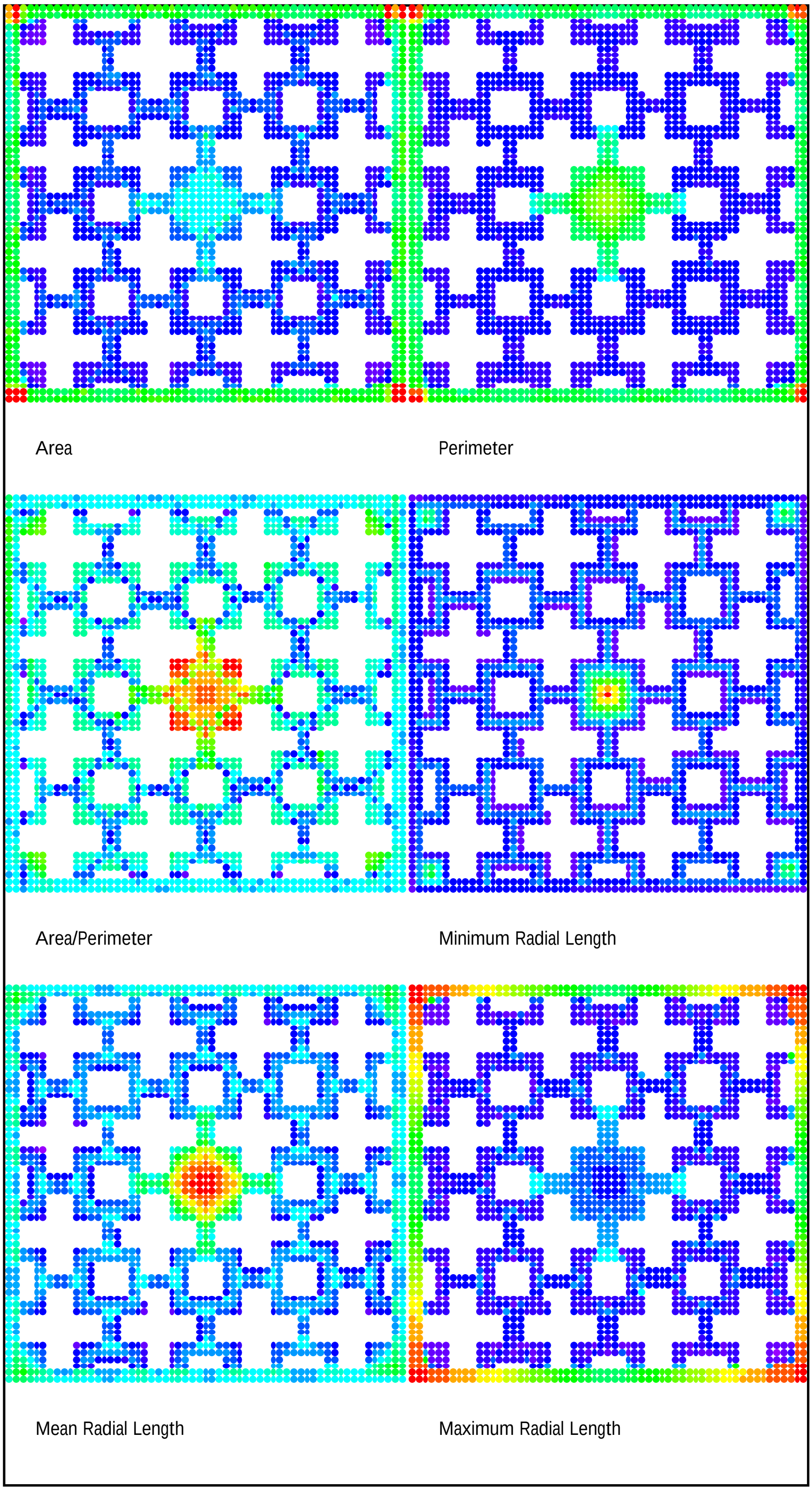


Figure 8.7 Isovist Attribute Maps for World B (Area, Perimeter, A/P, Minimum,Mean & Maximum Radial Lengths)

These values appear to form diagonal lines throughout the street network, these being the locations, where small, penetrating lines of sight connect one street to an adjacent street.

Minimum,Mean and Maximum Radial Length

Minimum radial length represents the distance from the isoivst viewpoint to the closest building. The location that is furthest from all buildings (and hence has the greatest 'minimum radial length' value) is the centre of the open square at the centre of the world. Maximum radial length can simply be considered a measure of the longest line of sight from the isovist viewpoint. The locations containing the longest lines of sight in World B are located at the corners of the world. Excluding the boundary roads, there are long lines of sight that pass through the central open space. In urban systems, the mean radial length of an isovist seems to be a fairly good indicator of road-junctions or locations where a route choice must be made. Again, the central open space in the centre of World B contains values much higher than elsewhere; although this space is an open market square it could be considered an unusually large type of junction. Because of the predominance of the open square there is less differentiation of isovist values within the street network but it is possible to discern slightly higher values of isovist mean radial length at the road junctions.

Standard Deviation,Variance and Skewness of Radial Lengths

The standard deviation of radial length is probably the most imformative of these three measures. This is a measure of the 'spread' of the radial lengths. Standard deviation is highest where there is greatest differention between the lengths of the radials of the isovists, for example at the corners of the world. These isovists are characterised as containing some of the longest and shortest radials; it is the difference between these values that is being measured. The isovists at the exact centre of the world are blue (low value) as the lengths of their radials are relatively uniform, whereas those isovists towards the edge of the central square contain a greater range of radial lengths. Since variance is the square of standard deviation, this measure emphasises the values at the upper end of the range, as does skewness.

Circularity, Drift and Dispersion

Circularity is a useful measure for identifying the 'roundness' of spaces, hence its name. The spaces within World B that most closely approximate a circle are those at the centre of the world and the smaller open spaces at each of the four corners of the world. The areas that least approximate circles are the boundary roads, which are long and thin. Areas of medium-high circularity appear to form diagonal lines criss-crossing the network of streets. This pattern resembles area/perimeter ratio since both are measures of 'roundness'.

Drift[7] indicates the distance between the isovist viewpoint and its centre of gravity. Drift will usually tend towards minimum values at the centre-lines of roads. The patterns of minimum drift in World B generate a set of 'lines' that resembles the axial break-up presented in Chapter 4. The areas of maximum drift are always located at the edges of wide, open spaces, where the centre of gravity is far from the viewpoint.

Dispersion is the difference between the mean radial length of an isovist and the standard deviation of its radials. This can also be held to be a good indicator

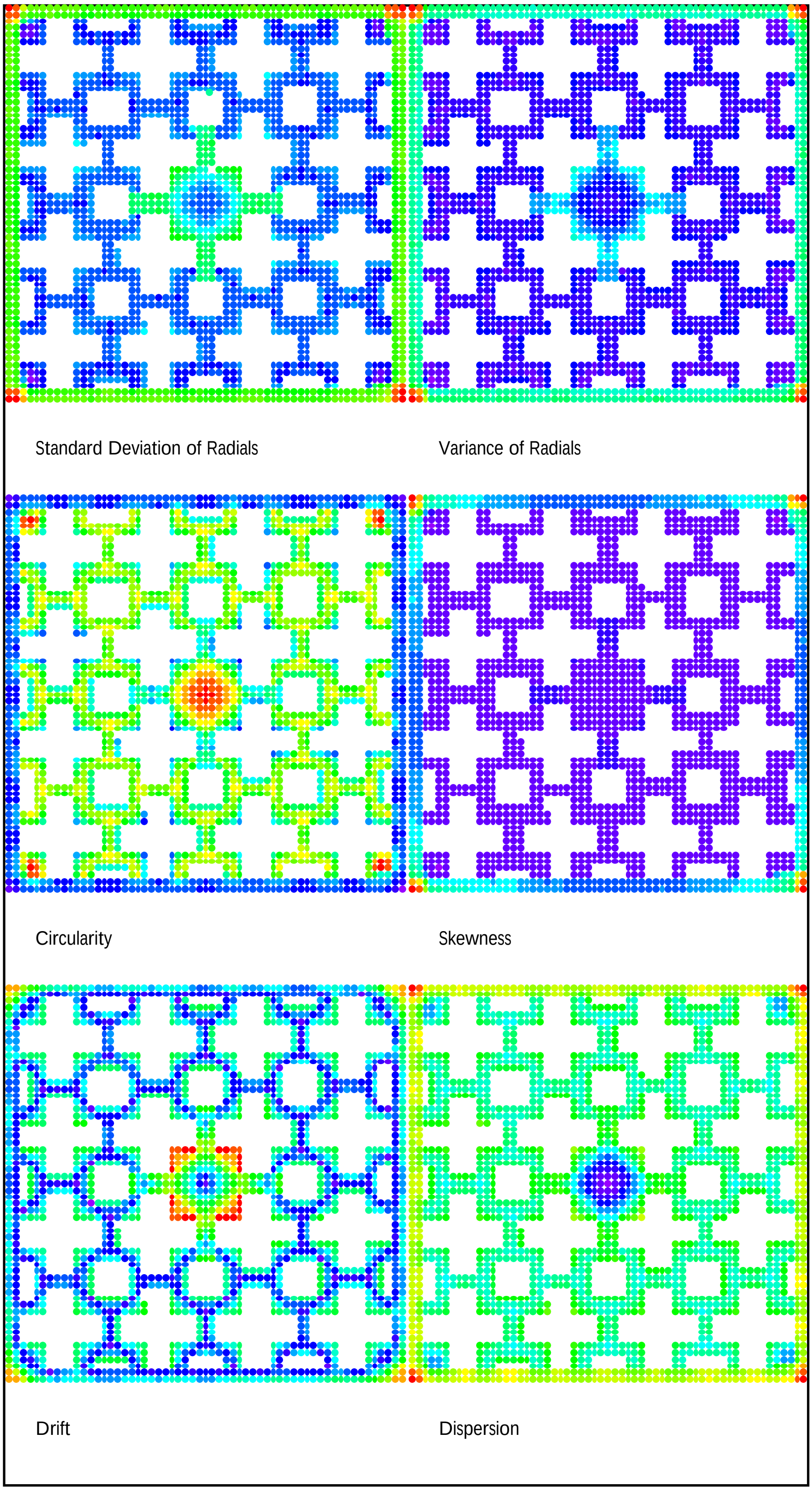


Figure 8.8 Isovist Attribute Maps for World B (Standard Deviation, Variance and Skewness of Radials, Circularity, Drift & Dispersion)

of ‘roundness’ or ‘spikiness’ of an isovist. Round spaces have low values of dispersion and long, thin spaces have high values of dispersion. In World B, the centre of the open space in the middle of the world contains isovists with values of lowest dispersion and the isovists at the corners of the world and within the boundary roads have the greatest dispersion values.

Syntactic Measures

The most integrating isovists are those situated at the corners of the world. These are also isovists with a high value of connectivity. It is clear from these diagrams that there is a relationship between connectivity and integration, particularly at the upper end of the range of values.

Pause Point Sampling

The table overleaf shows the results for the value of z as calculated by the central limit theorem and by the z-test. The results are ranked in descending order of z (from the z-test). There are only two isovist attributes which appear to have no effect upon people's stopping behaviours, these being standard deviation and variance of the isovist’s radials. If we were to consider the location of pause points with respect to these two isovist attributes then it would appear that people are pausing randomly. Since skewness is also derivied from these measures it is no surprise that this too has a low value of z.

At the upper end of the table, local and global integration both have quite high values of z. Consider the mean values of Radius 3 depth, total depth and mean depth for the pause point sample. People are pausing in locations with a *lower* mean value than the population of isovists. In other words people are tending to stop in locations which have a higher than average isovist integration value. Subjects appear to be far more likely to stop in integrated sections of the street network as these are the locations that are highly connected, offering a greater choice of route. Note that the mean connectivity of all pause point locations is 106.06 compared to the population as a whole which has a mean isovist connectivity of only 79.62.

Moving down the table, the next two measures are absolute dispersion and minimum radial length. Again, if the mean values for the sample and population are compared, it can be seen that people are pausing in locations with a higher than average absolute dispersion and higher than average minimum radial length. People are pausing in locations which are, on average, more than six metres from any occluding surfaces or built walls. In terms of the population as a whole, all isovists are, on average, only three metres from any buildings. If a subject were pausing in order to make a route choice decision, the further they are from any occluding surfaces, the more likely is that location to afford information-rich views. For example, if a person is trying to visually survey an area, it is unlikely that they would choose a location next to a large wall.

Further down the table, it can be noted that subjects are also pausing in locations with a greater average isovist area (1670.97m^2 compared to 1266.75 m^2) and higher isovist connectivity compared to the population. Since area and connectivity are related measures, if one measure has a signficant influence on stopping behaviour then the other should be influential. These results also support the observation that people are pausing in integrated locations, since these tend to be locations with more to see (a higher than average isovist area).

It can also be noted that subjects are pausing in locations of slightly greater circularity (more open, 'rounded' locations) and positions of below average drift (towards the centres of spaces and streets). They are also pausing in locations with a higher than average isovist perimeter value (locations of larger isovist area, containing more penetrating views) but with a slightly greater area/perimeter ratio (again more 'rounded' and open in shape). Finally, people are pausing in areas with longer than average maximum isovist radial lengths, locations which therefore permit more penetrating lines of sight. In other words, people are pausing efficiently; they are pausing in locations which offer them maximum information about their environment. In this way, they can pause less yet gather more knowledge of the environment each time and hence navigate the world with greater expediency. For the full table of results see overleaf.

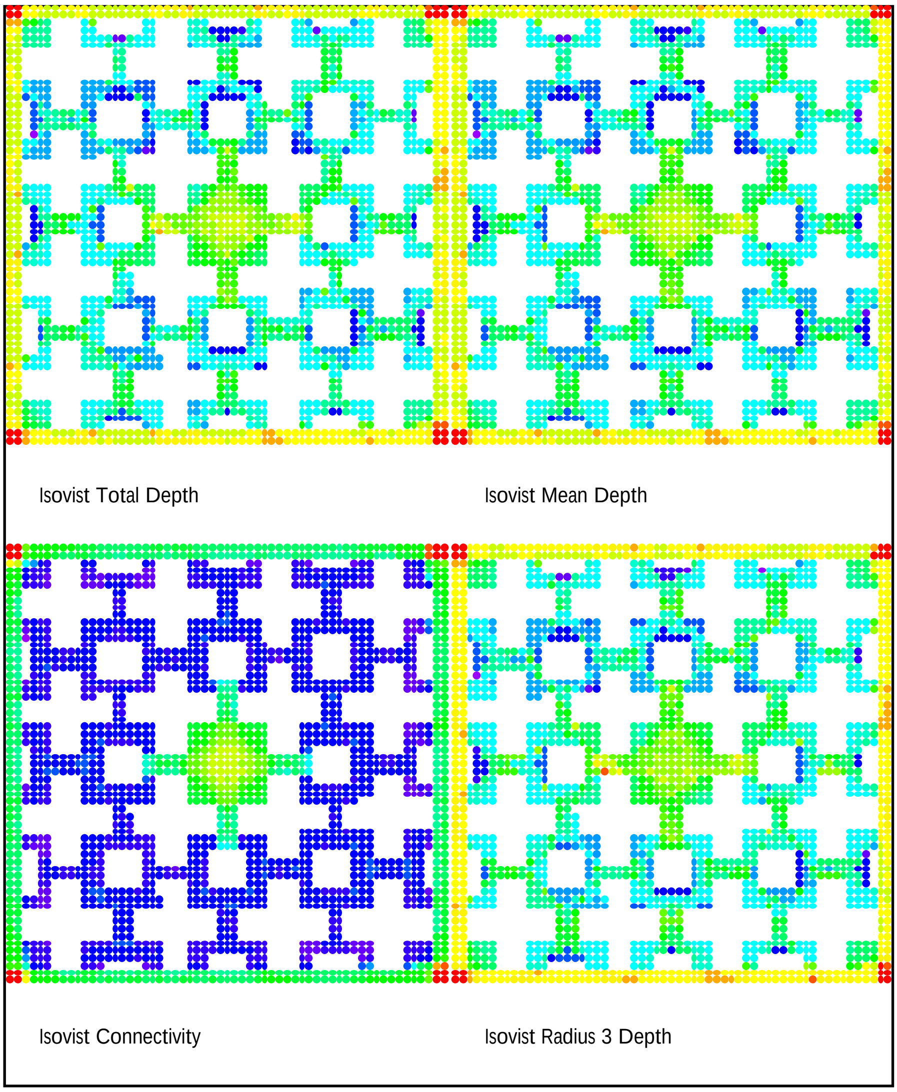


Figure 8.9 Isovist Attribute Maps for World B (Total Depth,Mean Depth,Connectivity & Radius 3 Depth)

Measure	Population mean	Sample (PP) mean	Population standard deviation	Sample (PP) standard deviation	Population variance	Sample (PP) variance	"Z" from c. l. t.	"Z" from Z-test
Total Depth Radius 3	5221.77	4709.13	1110.35	1014.06	1233500.67	1028313.29	-7.96	16.37
Absolute Dispersion	4.51	8.12	3.27	5.54	10.71	30.7	19.02	-10.95
Minimum Radius Length	3.07	6.63	2.24	5.64	5.04	31.77	27.36	-10.77
Mean Radius	13.88	17.21	3.28	5.46	10.78	29.81	17.49	-10.24
Total Depth	7239.54	6937.14	652.46	608.03	425919.25	369696.33	-7.99	7.9
Mean Depth	3.72	3.56	0.34	0.31	0.11	0.1	-7.99	7.83
Area	1266.75	1670.97	735.49	850.81	541226.58	723874.78	9.47	-7.76
Connectivity	79.62	106.06	47.06	57.16	2215.51	3267.26	9.68	-7.59
Circularity	0.56	0.64	0.16	0.22	0.03	0.05	8.79	-6.2
Dispersion	-0.48	-3.79	5.55	9.08	30.85	82.51	-10.27	6.11
Drift	3.96	3.07	2.31	2.33	5.34	5.41	-6.59	6.11
Perimeter	297.85	354.41	158.49	160.19	25131.67	25660.47	6.15	-5.68
Area/Perimeter	4.26	4.7	1.07	1.51	1.15	2.27	7.07	-4.84
Maximum Radius Length	78.51	94.09	58.23	68.78	3392.68	4730.35	4.61	-3.71
Radial Skewness	14729.72	19671.23	26588.29	30313.33	707300495.78	918897837.21	3.2	-2.66
Radial Variance	214.22	226.14	193.61	214.36	37503.03	45950.57	1.06	-0.9
Radial Standard Deviation	13.4	13.42	5.89	6.8	34.72	46.18	0.06	-0.05

Table 8.4 Tabulated Population and Sample Data from World B

World C

Area, Perimeter and Area/Perimeter

In World C, locations of greatest isovist area are at the corners of the boundary roads. At these locations the isovist area is approximately equivalent to the area of two of the four boundary roads and hence offer the largest unoccluded views anywhere in this world. Excluding the boundary roads, the location in World C which has the highest values of isovist area is the 'open square' at the centre of the world (the wayfinding goal) and the streets leading from it. This pattern is mirrored by the isovist measure perimeter. The space with the greatest isovist perimeter is the central square since the six roads radiating from it create an extremely 'spiky', six-pointed isovist. Area/perimeter is one of the measures that indicates the 'spikiness' or 'roundness' of an isovist. Although the boundary roads are patently not 'round' but thin and rectangular, they are less spiky than many of the junctions (which produce quite star-shaped isovists).

Minimum, Mean and Maximum Radial Length

Minimum radial length is a wonderfully simple measure of 'open space'. In World C the most open space is the 'square' where the market cross is. This is practically the only open space in this world, apart from an occasional widening of some of the roads. Maximum radial length is a measure of the longest line of sight in any direction. The longest lines of sight in World C occur at the corners of the world, where there are unobstructed views to adjacent corners. However, the most significant line of sight in World C is the single line that connects one side of the world with the other, passing through the central square at a diagonal angle. This line is probably the most important line of sight in this world and it emerges clearly from this analysis.

In World C, the isovists with highest mean radial length are in the central open 'square'. Other 'pockets' of high mean radial length are distributed throughout the world and are clearly discernible from figure 8.10. These small pockets tend to be located at the intersections of roads. Although many

Figure 8.10 Isovist Attribute Maps for World C (Area, Perimeter, A/P, Minimum,Mean and Maximum Radial Length, Standard Deviation & Variance of Radials)

Figure 8.11 Isovist Attribute Maps for World C (Circularity, Skewness,Drift, Dispersion,Total Depth,Mean Depth, Connectivity & Radius 3 Depth) of them are not significantly high in value (unlike the central square), they can be identified by having a higher value than the immediate surrounding area (i.e. local maxima).

Standard Deviation, Variance and Skewness of Radial Lengths

The isovist viewpoints with the highest value of standard deviation of radial lengths are located at the corners of the world, which are coloured red on plan. Other isovists with radials of higher than average standard deviation are to be found at the boundary roads and along the main diagonal road leading from the central market 'square'. This distribution of values is accentuated in the diagram which shows the distribution of values for isovist radial variance. The areas of high values of isovist variance are at the corners and the edges of the world; the central square in the middle of the world and the six streets radiating from it become more dominant than before.

Circularity, Drift and Dispersion

The pattern of drift in World C is quite revealing since it could be regarded as indicating 'the shortest paths' through the network of streets. Therefore it could be suggested that the patterns formed by the areas of minimum drift in an urban system could represent potential minimum-distance routes[8] through the street system. By visualising the patterns of drift in World C, certain paths through the network emerge quite dramatically.

Syntactic Measures

The corners of the boundary roads and certain junctions appear to be integrated in World C, when analysed sytactically. The most integrated location in World C is the open square at the centre of the world. The most segregated locations, in terms of isovist integration, are some of the narrow side-streets to the left of the world on plan. Although the central space is the most integrated in the world, it is not the most highly connected. Since there is a high correlation between the connectivity and area of an isovist and since the boundary-corners of World C have high values of isovist area then they will be likely to highly connected. Radius 3 depth (the local integration measure) provided quite a striking result: the predominant feature of this value is the red, six-pointed star of integration that appears at the centre of the world.

Pause Point Sampling

After performing both the z-test and central limit theorem calculations, three isovist attributes emerged as having little or no effect upon the location of pause points. In other worlds, in terms of these three attributes, the pause point locations could have been generated randomly. These attributes are area/perimeter, maximum radial length (longest line of sight) and standard deviation of radial length. At first, this seems rather surprising since, in particular, maximum radial length appeared to have been significant in determining where subjects pause in the other worlds. However, the distribution of population isovist measures may have been weighted by the particularly high values of maximum radial length found at the corners of the world.

The two values that appear to have had greatest influence on where people paused are the attributes drift and minimum radial length. These two values are related since they both represent (albeit slightly differently) the distance from an occluding edge or

Measure	Population mean	Sample (PP) mean	Population standard deviation	Sample (PP) standard deviation	Population variance	Sample (PP) variance	"Z" from c. l. t.	"Z" from Z-test
Drift	6.72	3.26	3.8	2.45	14.48	6.03	-10.03	14.88
Minimum Radius Length	5.13	9.72	3.45	4.2	11.9	17.64	14.7	-11.92
Radius 3 Total Depth	1500.51	728.7	1580.83	861.5	2499794.74	742183.93	-5.39	9.32
Dispersion	4.54	-0.49	6.47	6.05	41.82	36.6	-8.59	8.99
Mean Depth	2.57	2.38	0.31	0.25	0.1	0.06	-6.67	8.27
Total Depth	8314.59	7701.77	1015.03	807.41	1030603.74	651913.07	-6.67	8.14
Circularity	0.45	0.52	0.1	0.09	0.01	0.01	7.83	-7.57
Mean Radius	26.26	31.08	7.69	7.58	59.18	57.5	6.93	-6.9
Absolute Dispersion	12.72	3.64	7.23	3.15	54.07	9.95	-13.89	6.12
Radial Skewness	127843.1	88949.65	142689.12	74684.07	20366470123.2	5577710729.16	-3.01	5.39
Perimeter	653.26	791.82	258.41	330.3	66796.58	109097.01	5.92	-4.58
Mean Depth Radius 3	3.98	3.44	0.3	1.39	0.09	1.93	-19.88	4.25
Connectivity	341.4	378.14	187.75	139.2	35261.91	19376.96	2.16	-2.82
Area	5540.38	6103.03	3090.52	2211.73	9554254.77	4891759.61	2.01	-2.71
Radial Variance	1066.62	973.32	691.56	382.54	478402.78	146336.99	-1.49	2.54
Maximum Radius Length	181.16	177.73	80.29	62.07	6449.19	3852.41	-0.47	0.59
Radial Standard Deviation	30.79	30.59	10.88	6.16	118.43	37.97	-0.21	0.35
Area/Perimeter	7.96	7.98	2.42	2.09	5.86	4.35	0.09	-0.11

Table 8.5 Tabulated Population and Sample Data from World C

built surface. It is no surprise that people are pausing in the centres of spaces, particularly since, in a virtual world, there exists nothing to discourage subjects from walking along the middle of roads, such as vehicles. In addition to this fact, pausing any distance from an occluding surface will allow a greater view of the surrounding area. In World C, people were stopping an average of 9.72m from a building compared to a population average of 5.13m. It should also be noted that people are pausing at locations with a higher than average value of circularity (0.52 compared to 0.45). As this can also be held to be a measure of distance from a built edge (combined with shape of isovist), then this finding is linked to the results for drift and minimum radial length.

The factors that seem to greatly affect the locations of pause points in World C, are the syntactic measures. People are pausing in more integrated locations, in terms of Radius 3 depth, mean depth and total depth. This is similar to the findings of other worlds. It can also be observed that people are pausing in locations that contain more connected isovists (378.14 compared to 341.40) which is obviously also related to an isovist's measure of area; people are pausing in locations with isovists of a larger than average area (6103.03 square metres compared to 5540.38 square metres). Refer to table 8.4 for the full set of statistics for World C.

World D

Area, Perimeter and Area/Perimeter

Like World C, the isovists with the greatest area in World D are located at the corners of the world. What is quite striking about World D, in comparison to World C, is that there is little variation in the values of isovist area within the network of streets. This is unlike the interior of World C, which contained a far greater range of values of isovist area. Similar to isovist area, the isovists with the largest perimeter are located at the corners of the world. The areas of high isovist perimeter (excluding the boundary roads) appear to be located at road junctions. Area/perimeter ratio is one of the families of measures indicating the 'roundness' or 'spikiness' of an isovist. The isovists with the highest area/perime-

Figure 8.12 Isovist Attribute Maps for World D (Area, Perimeter, A/P, Minimum,Mean and Maximum Radial Length, Standard Deviation & Variance of Radials) ter values are found at the bottom edge of the world, on plan. Within the street network, the equivalent space to the 'square' in World C, also emerges as having a slightly higher than average set of isovist area/perimeter values.

Minimum, Mean and Maximum Radial Length

World D contains a greater range of values for isovist minimum radial length compared to World C, due mainly to the irregularity of street widths in this world. The measure maximum radial length, in contrast, is an estimate of the longest line of sight perceivable from an isovist's viewpoint. Once again, similar to World C, the locations whose isovists contain the longest lines of sight occur at the corners of the world. However, indicators of long lines of sight can be seen within the interior of the world as well, although, there is no single, predominate line of sight as in World C.

Standard Deviation, Variance and Skewness of Radial Lengths

Standard deviation, variance and skewness of radial lengths all follow a similar pattern of distribution throughout World D, with the higher end of the values being located towards the edges of the world. The higher than average values of each isovist attribute are concentrated in the corners of the world, with the mid-range values being located along the boundary roads. Locations containing the lower end of the range of values are to be found within the network of streets at the centre of the world. There is little differentiation between values at the lower end of the spectrum. Such uniformity of values in the street network within World D is emphasised when visualising the distribution of variance and skewness. For the values of skewness, there is almost no perceptible differentiation within the interior of the world. This is similar to World C, but a far more marked phenomenon in World D

Circularity, Drift and Dispersion

Circularity and dispersion both accentuate the 'rounded', unoccluded or non-spiky spaces within a system. The measure circularity highlights 'rounded' spaces by colouring them red whereas dispersion represents these qualities as blue. The least rounded or most spiky spaces are those which are located at the corners of the world. The space with the highest circularity value is the open square in the centre of World D, which was the site of the monument or wayfinder's goal. Drift, once again, produces an interesting pattern. The network of streets and their connections are easily discernable from the distribution of this attribute. Note also, the manner in which the lowest values of drift bend around corners and diagonally 'traverse' open spaces. Could the values of minimum-drift perhaps be indicative of some type of minimum path[9] from which the entire world is visible?

Syntactic Measures

Isovists with high minimum depth values, namely areas of maximum local and global integration are all located at the corners of the world. The least integrated isovists in World D are all in the interior of the street network. It is difficult to discern any predominant structure to the distribution of the integration values, unlike World C. This could be because World D is a far less intelligible world[10] than World C and this emerges from the analysis. There is also little differentiation in the values of isovist connectivity for World D (similar to the results for isovist area). The isovists that are the

Figure 8.13 Isovist Attribute Maps for World D (Circularity, Skewness, Drift, Dispersion, Total Depth, Mean Depth, Connectivity & Radius 3 Depth) most highly connected in this world are those on the boundary of the world.

Pause Point Sampling

In this world, there are a number of isovist attributes that appear to have played little or no role in influencing subjects' pausing behaviour. This is the only world in the sample of seven, where so many isovist attributes appear to have had no effect upon the location of pause points, such that these locations could have been selected randomly. In particular, the syntactic isovist measures of mean depth, total depth, Radius 3 depth and connectivity appear to be irrelevant in terms of their influence on stopping behaviour. This is a particularly significant result, since this world was designed by Hillier to be an example of an unintelligible environment. The fact that people are pausing randomly in terms of the measures of the isovist visibility graph, suggest that this may be because these measures themselves are uninformative in this particular environment. If the measures themselves are meaningless, then it is entirely appropriate that they have little or no influence upon navigation.

Measures that appear to have greatest effect upon the location of pause points in this world are the isovist attributes drift and minimum radius length. This result was also found in World C. In World D people are pausing on average 9.90m from a built edge compared to an average of 5.98m for the population. Equally, since smaller values of drift tend towards the centres of spaces and roads, then it can be seen that people are pausing in locations far away from any buildings (locations with an average drift value of only 2.61m compared to the population mean of 7.70m).

In World D, a rather surprising result is that people appear to be pausing in locations with shorter than average lines of sight. This appears to contradict previous findings. However, since the areas of highest maximum radial length (longest line of sight) are concentrated in the corners of the world, where few people paused at all, then this could account for this rather anomalous result.

Since dispersion and circularity belong to the same family of measures, those indicating 'roundness' or the unoccluded nature of a space, then it is appropriate that they should appear sequentially on the table. The sample of isovists at pause point locations appear to have a higher than average value of circularity (0.55 compared to 0.49) and a lower than average value of dispersion (-1.13 compared to 2.55). This indicates that people are tending to pause at the centres of open spaces in World D. This appears to be an appropriate finding if considered from a navigational perspective. It could be hypothesised that it is a common reaction to pause momentarily when emerging suddenly from a confined or visually limited space into an open space. Pausing in the centres of spaces also afford the greatest visual information about that space.

Measure	Population mean	Sample (PP) mean	Population standard deviation	Sample (PP) standard deviation	Population variance	Sample (PP) variance	"Z" from c. l. t.	"Z" from Z-test
Drift	7.7	2.61	4.48	2	20.1	3.99	-9.9	21.09
Minimum Radius Length	5.98	9.9	4.13	2.65	17.02	7.01	8.28	-12.58
Maximum Radius Length	176	137.5	86.64	46.68	7508.48	2179.31	-3.87	6.94
Radial Skewness	135806.67	73509.01	169477.87	76617.29	28730907297.3	5870208921.33	-3.2	6.74
Dispersion	2.55	-1.13	7.35	7.62	54	58.06	-4.36	4.16
Circularity	0.49	0.55	0.12	0.14	0.01	0.02	4.47	-3.66
Mean Radius	28.29	29.99	9.3	4.53	86.55	20.51	1.59	-3.13
Radial Variance	1116.14	921.74	860.58	529.91	740810.42	280808.37	-1.97	3.11
Perimeter	636.21	596.8	258.63	146.23	66909.64	21383.33	-1.33	2.27
Area/Perimeter	8.75	9.45	3.2	2.66	10.24	7.09	1.92	-2.27
Radial Standard Deviation	30.83	28.86	12.86	9.48	165.41	89.92	-1.34	1.78
Mean Depth	2.7	2.65	0.35	0.27	0.12	0.07	-1.34	1.71
Total Depth	9519.68	9333.53	1215.24	944.1	1477226.06	891332.63	-1.34	1.69
Area	6137.17	5706.21	4016.23	2313.35	16134704.54	5351582.39	-0.94	1.57
Connectivity	374.28	351.38	243.02	141.82	59077.83	20112.51	-0.82	1.37
Radius 3 Total Depth	2714.26	2536.82	1869.24	1322.15	3495050.96	1748078.29	-0.83	1.15
Absolute Dispersion	5.76	5.83	5.22	4.99	27.28	24.91	0.11	-0.12
Mean Depth Radius 3	4	4	0	0	0	0	0	0

Table 8.6 Tabulated Population and Sample Data from World D

World E

Area, Perimeter and Area/Perimeter

The isovists with the greatest area are those at the centre of World E, in the open space (unlike previous worlds this was not used as a wayfinding goal. The subjects were instructed to traverse the world from one corner to the opposite corner). The boundary roads and the junctions of roads also have higher than average values of isovist area. In contrast to the measure isovist area, the locations whose isovists have the longest perimeter are those at the corners of the world. Again, the central space and the road-junctions have high perimeter values. Area/perimeter is a measure that selects open, 'rounded' spaces and hence there is little differentiation of values within the street network; the locations whose isovists have the highest value of all are those viewpoints situated in the open spaces.

Minimum, Mean and Maximum Radial Length

Minimum radial length is a measure of the distance from the viewpoint of an isovist to its nearest occluding surface. Since all of the streets in World E are of equal width, the roads all have, more or less, the same value. The only isovists in the world that are any great distance from a building are those in the central, open space. The measure maximum radial length identifies the longest lines of sight that are available in the world. In World E, the longest lines of sight stretch from one corner of the world to adjacent corners. In addition to this, there are long lines of sight that pass through the central open space. Mean radial length, is a measure that is a good indicator of road junctions. In World E, the junctions emerge as patches of green against the dark blue of the street network. The centre of the world also contains isovists with particularly high values of mean radial length.

Standard Deviation, Variance and Skewness of Radial Lengths

The isovist locations in World F with the greatest standard deviation of radial length are those at the corners of the world. The boundary roads and the central space have higher than average values of

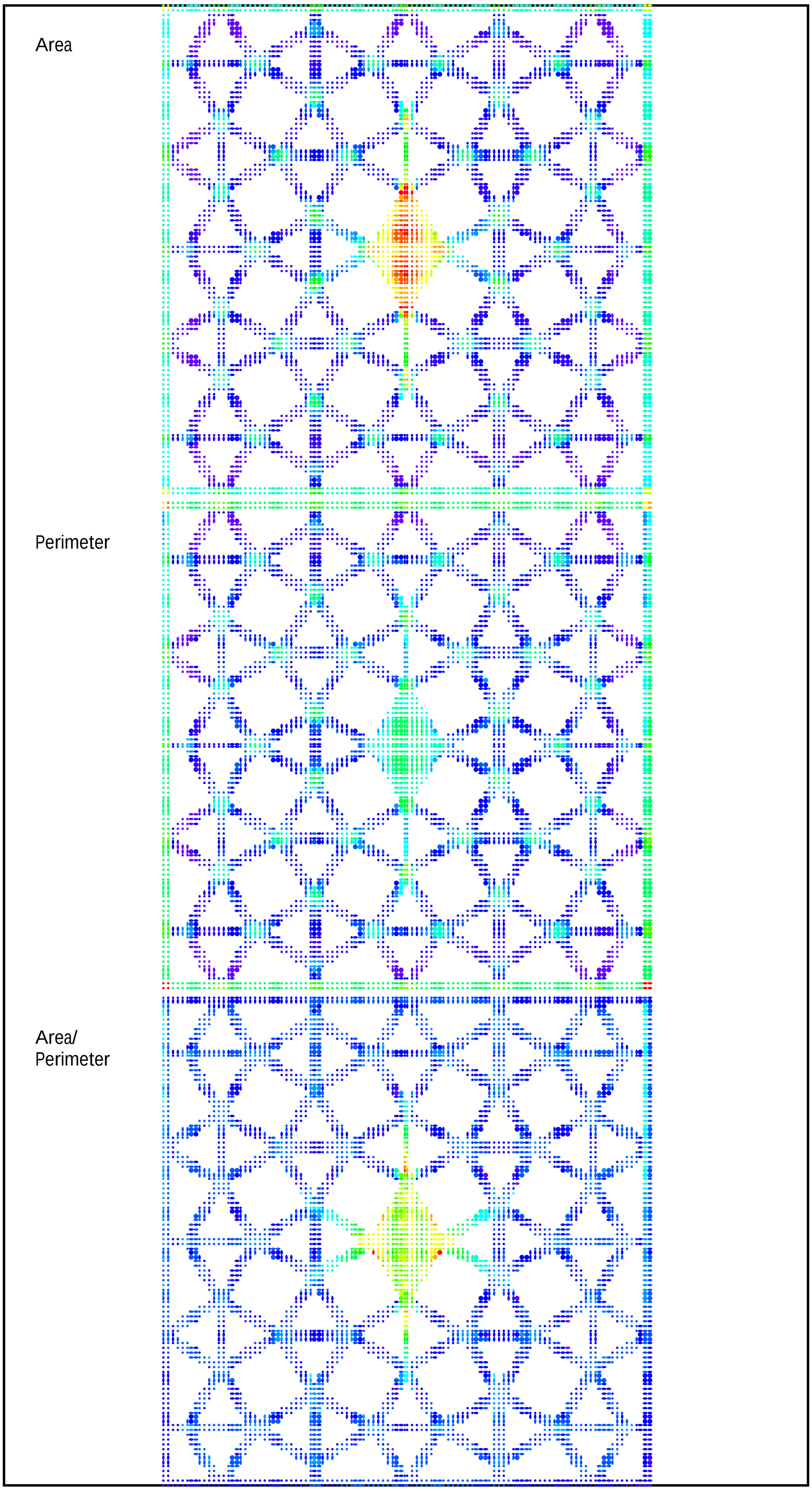


Figure 8.14 Isovist Attribute Maps for World E (Area, Perimeter & A/P)

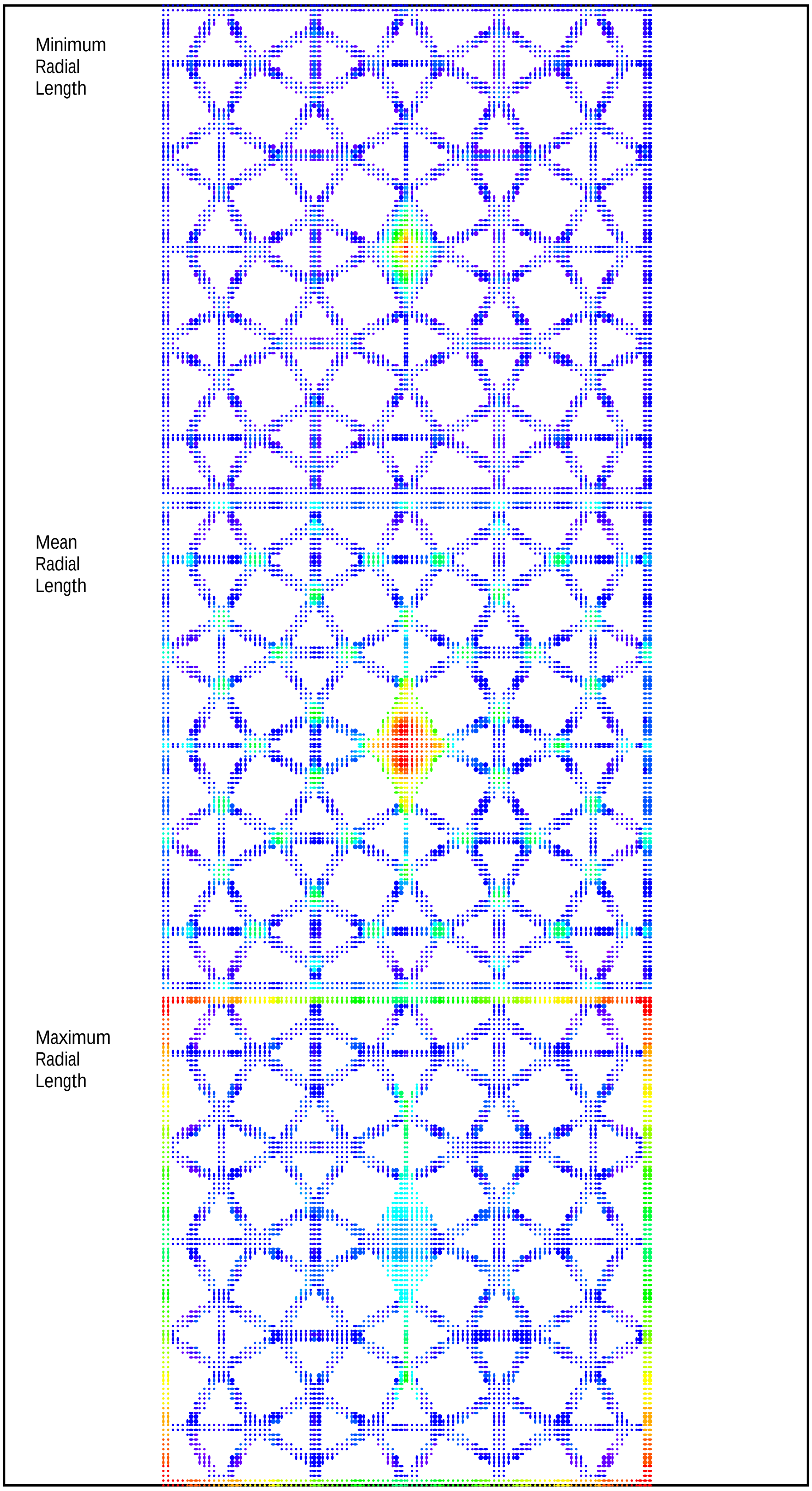


Figure 8.15 Isovist Attribute Maps for World E (Minimum,Mean & Maximum Radial Length)

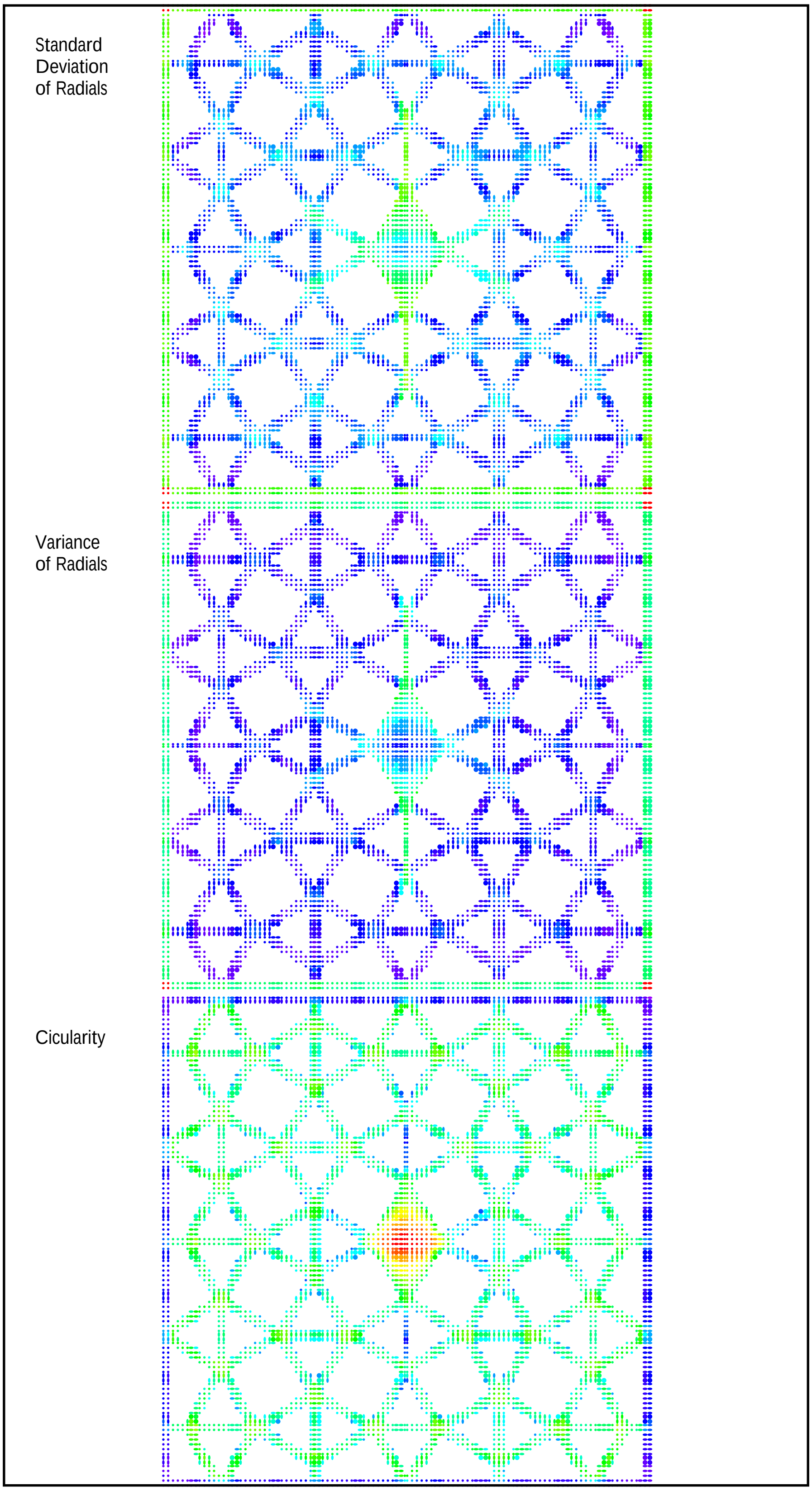


Figure 8.16 Isovist Attribute Maps for World E (Standard Deviation & Variance of Radials & Circularity)

radial standard deviation. The relationship between the distributions of the values of standard deviation, variance and skewness, is that the latter two measures highlight those isovists with higher values of standard deviation and 'even out' or dampen the values at the lower end of the spectrum. The representation of radial variance shows a smaller range of values in the interior of the world compared to the representation of standard deviation. The visualisation of skewness, only picks out the outer boundary as having higher than average values; the street network is almost uniformly low.

Circularity, Drift and Dispersion

Circularity is not only a measure of the shape of a space but it is a measure of how centrally the viewpoint of the isovist is situated within that space. In World E, the spaces with the highest values of centrality are those at the centre of the world. The spaces with the lowest values of centrality are found in the boundary roads at the edge of the world. The road junctions are just perceivable through a slight increase in their values of isovist centrality compared to the streets radiating from the junctions (local maxima). Since drift tends towards a minimum value at the centres of spaces and along the centrelines of roads and since the roads of World E are of equal width, the majority of spaces in World E have a low value of drift. The only locations with a high value of drift are the spaces at the edges of the large, open space at the world's centre. These are all locations which command a larger than average isovist and whose centre of gravity is at quite a distance from the isovist's viewpoint.

Syntactic Measures

The locations that are the most globally integrated in World E are to be found at the corners of the world and along the boundary roads. The other patches of highly integrated spaces are located at the centre of the world, both at the exact centre of the main open space and at either end of the vertical line of sight passing through the central open space. The most globally segregated areas are in the street network and yet only a couple of steps from the integrated outer boundary road. The pattern of connectivity is similar to the pattern of global integration, with the central space being extremely well connected. In terms of isovist connectivity, the central location is of greater import than the outer boundary and its corner locations. The road junctions also emerge visually, as being better connected than the adjacent streets.

Pause Point Sampling

Syntactic isovist measures seem to be the prime factor influencing stopping behaviour in this world. By referring to table 8.18, it can be seen that the isovist attributes with the greatest value of z are total depth, mean depth, radius 3 depth and connectivity. Essentially people are pausing in locations that are a fewer number of visual steps away from everywhere else in the system (more visually integrated). This finding supports the hypothesis that if you become lost *but* are in a segregated location it is less useful to stop immediately. It is far better to wait until you emerge into a more integrated space, then pause and take stock of your surroundings. It can also be seen from the table that people are pausing, in World E, in locations with more than twice the average connectivity of the world (316.75 versus 142.44 mean connections).

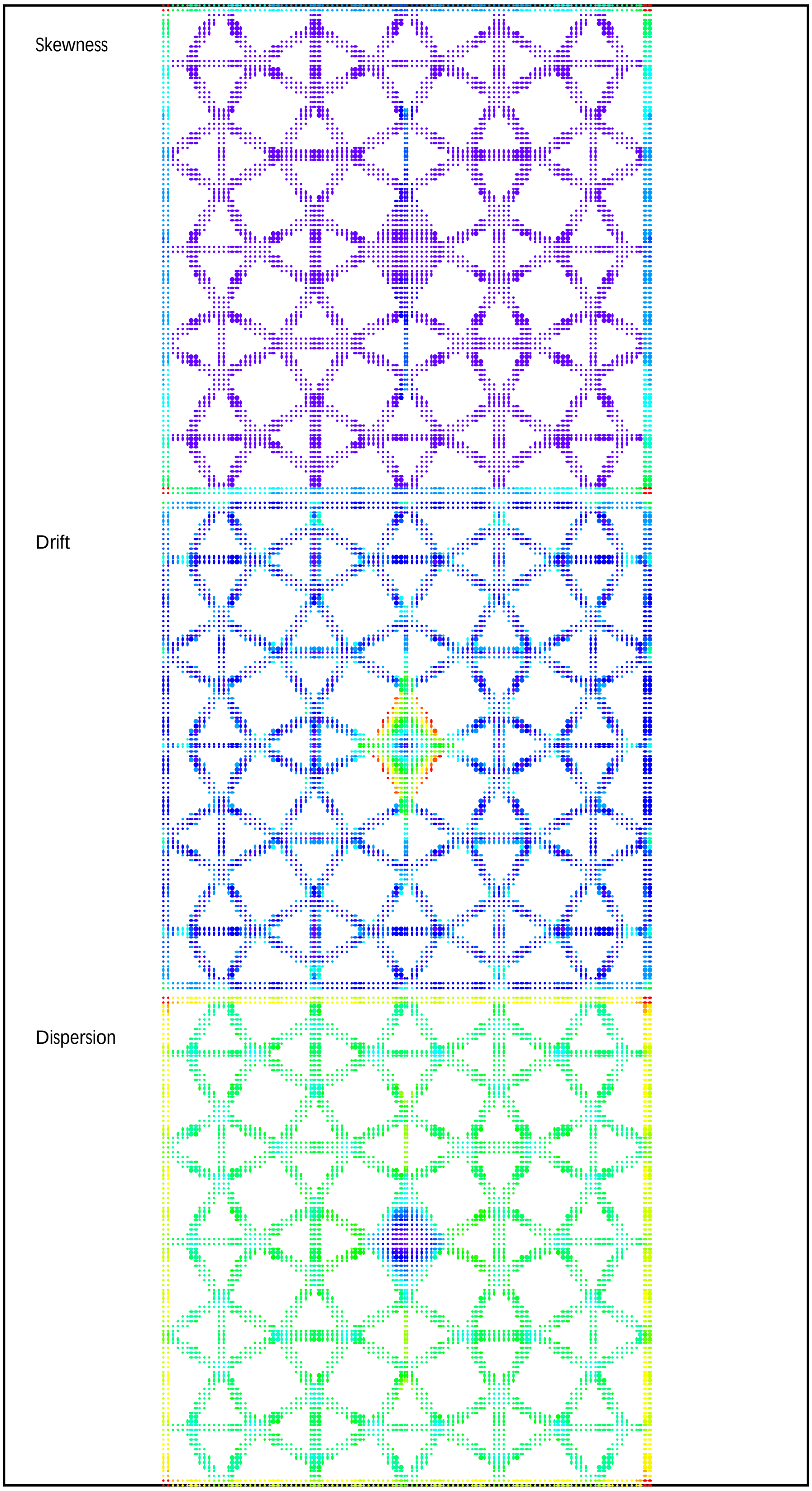


Figure 8.17 Isovist Attribute Maps for World E (Skewness of Radials,Drift & Dispersion)

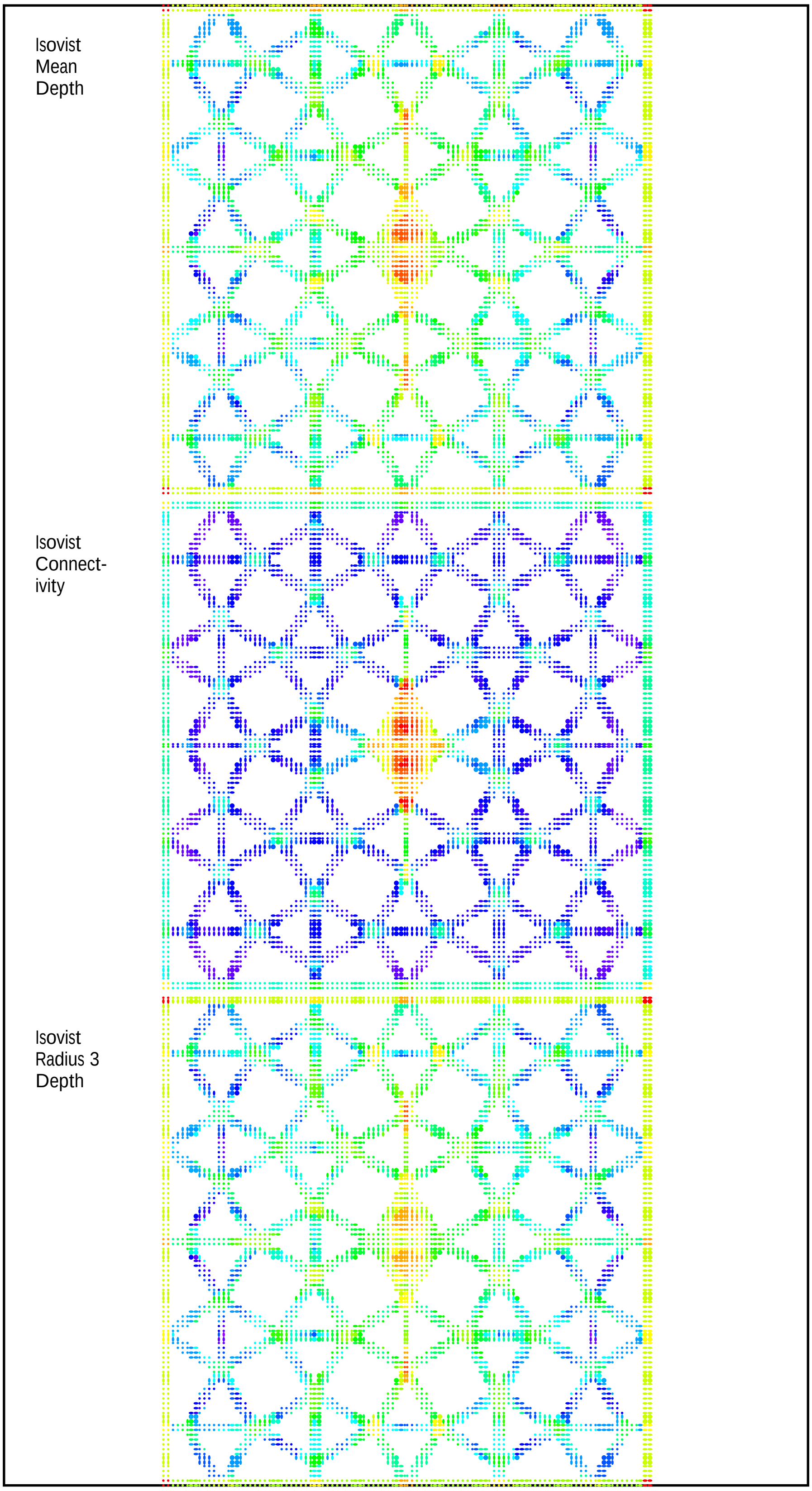


Figure 8.18 Isovist Attribute Maps for World E (Mean Depth,Connectivity & Radius 3 Depth)

Subjects appear to be selecting locations in which to pause that have particularly strategic lines of sight passing through them. This can be deduced from the fact that people are pausing in locations with significantly larger isovist perimeter values than the isovist population of World E and that these are also locations containing much longer lines of sight. The average length of the greatest line of sight from any location in World E is 198.06m. The average length of the maximum line of sight for the sample of pause point locations is 549.38m. These lines are, on average, 277% longer. Locations with particularly long lines of sight would be more strategic locations from which to scrutinise the environment whilst wayfinding. Standard deviation of radial length is a measure that is also linked to perimeter length and to maximum radial length, signifying as it does, a type of isovist ‘spikiness’ (see the table at the beginning of this chapter, illustrating their relationship to other measures). The pause point locations of subjects in World E have almost double the standard deviation of their radial lengths than the population of world isovists.

In World E, the results for drift, circularity and minimum radial length appear to be at odds with the results found for the rest of the worlds so far. In other worlds, it was noted that people tended to be pausing in locations with much lower drift, higher circularity and higher minimum radial length. This indicated that they were pausing in the centres of spaces (smaller drift values) and as far from occluding surfaces as possible. This is the pattern found in all seven of the test environments bar two; World E and World F. It should be noted from Chapter 4, that these were the two worlds in which the subjects were allowed to move at an accelerated pace (akin to jogging instead of walking). It could be suggested that this change of pace might provide an argument for this different pattern. It has already been suggested in Chapter 7 that this change of pace affected the duration of the subject’s pauses, namely that they were pausing for shorter amounts of time compared to the other worlds. Consequently, it may not be too great a supposition to suggest that this change of pace might also be reflected in the actual locations where people were stopping. Furthermore, it was noted whilst monitoring subjects’ progress on a separate computer monitor, during the course of the experiments, that the change in pace seemed to induce a certain eccentricity of movement. Moving at a greater pace gave subjects less time to make finer-scale navigational adjustments. Again, from purely informal observations, it seemed that subjects were more likely to bump into walls, when moving at an accelerated pace. Since the incident of collisions was not recorded in any manner, this is purely a remembered phenomenon. However, it might provide an explanation for the statistical results of the pause point sampling data. It should be noted that if these experiments were to be repeated then it would be advisable to restrict subjects to a walking pace at all times, regardless of reasons to permit otherwise (see Chapter 4, for the reasons for allowing this change).

Measure	Population mean	Sample (PP) mean	Population standard deviation	Sample (PP) standard deviation	Population variance	Sample (PP) variance	"Z" from c. l. t.	"Z" from Z-test
Total Depth	18879.73	15823.67	1598.09	1208.17	2554394.4	1459675.25	-19.12	24.87
Mean Depth	3.74	3.13	0.32	0.24	0.1	0.06	-19.12	24.32
Radius 3 Total Depth	13663.61	8319.9	2684.57	2229.35	7208366.61	4970013.99	-19.91	23.63
Area	5166.28	11062.24	3258.63	2718.62	10620778.93	7390901.91	18.09	-21.39
Connectivity	142.44	316.75	89.48	82.1	8008.61	6739.95	19.48	-20.99
Perimeter	781.28	2014.06	369.78	598.83	136765.54	358603.14	33.34	-20.51
Radial Standard Deviation	30.49	59.47	10.23	14.35	104.6	205.98	28.34	-20.09
Maximum Radius Length	198.06	549.38	139.83	174.92	19556.86	30597.88	25.12	-19.96
Radial Variance	1034.35	3740.47	724.18	1520.98	524542.85	2313379.09	37.37	-17.75
Absolute Dispersion	8	33.9	8.81	15.19	77.61	230.88	29.4	-16.99
Radial Skewness	164076.61	1632222.74	286961.47	910782.61	82363199764.5	829524970229	51.16	-16.1
Dispersion	5.33	32.14	10.64	18.67	113.25	348.64	25.2	-14.31
Drift	5.68	11.75	4.02	4.34	16.14	18.85	15.09	-13.84
Circularity	0.43	0.24	0.13	0.15	0.02	0.02	-15	13.13
Area/Perimeter	6.41	5.71	1.7	1.44	2.9	2.08	-4.11	4.79
Mean Depth Radius 3	4.01	4	0.08	0	0.01	0	-0.8	4.5
Mean Radius	25.16	27.33	9.22	6.59	84.98	43.44	2.35	-3.23
Minimum Radius Length	4.7	4.76	4.2	3.22	17.65	10.4	0.14	-0.18

Table 8.7 Tabulated Population and Sample Data from World E

World F

Area, Perimeter and Area/Perimeter

The pattern for the distribution of isovist area values in World F is quite predictable; the isovists of largest area are to be found at the corners of the world where there are large, open spaces. The areas of greatest isovist perimeter in World F are located at the crossroads of the longest streets in this world. At these locations, the shape of the isovists would resemble particularly long-fingered, four-pointed stars. The areas with the smallest isovist perimeter values appear to be at the side streets that terminate with T-junctions at both ends. The pattern of greatest isovist area/perimeter values for World F is interesting; the streets within the interior of the world all have a similar value of area/perimeter ratio. The 'perfect' squares inside the world all have a slightly higher than average value. Note how the darker blue values of the streets remain uniformly blue even as a street passes through an open square. The locations with the highest area/perimeter values are all located in the open spaces at the corners of the world. Note how the highest values increase towards the primary occluding surfaces of the open square.

Minimum, Mean and Maximum Radial Length

Minimum radial length is simply a measure of how close to a built surface is an isovist's viewpoint. The results of this analysis, as to be expected with the seven open spaces or squares in this world, produce visually striking results. Three of these open spaces are square in plan, the other four, non-square spaces are each located in a corner of World F. Maximum radial length is a measure of the length of the longest line of sight in any direction available from the viewpoint of an isovist. Excluding the four boundary roads, the areas of maximum radial length are located at the ends of the three roads in World F, which span from one side of the world to the other. The areas of least isovist maximum radial length are located at the centres of the shortest streets in the world; these are the streets that terminate at T-junctions at both their ends.

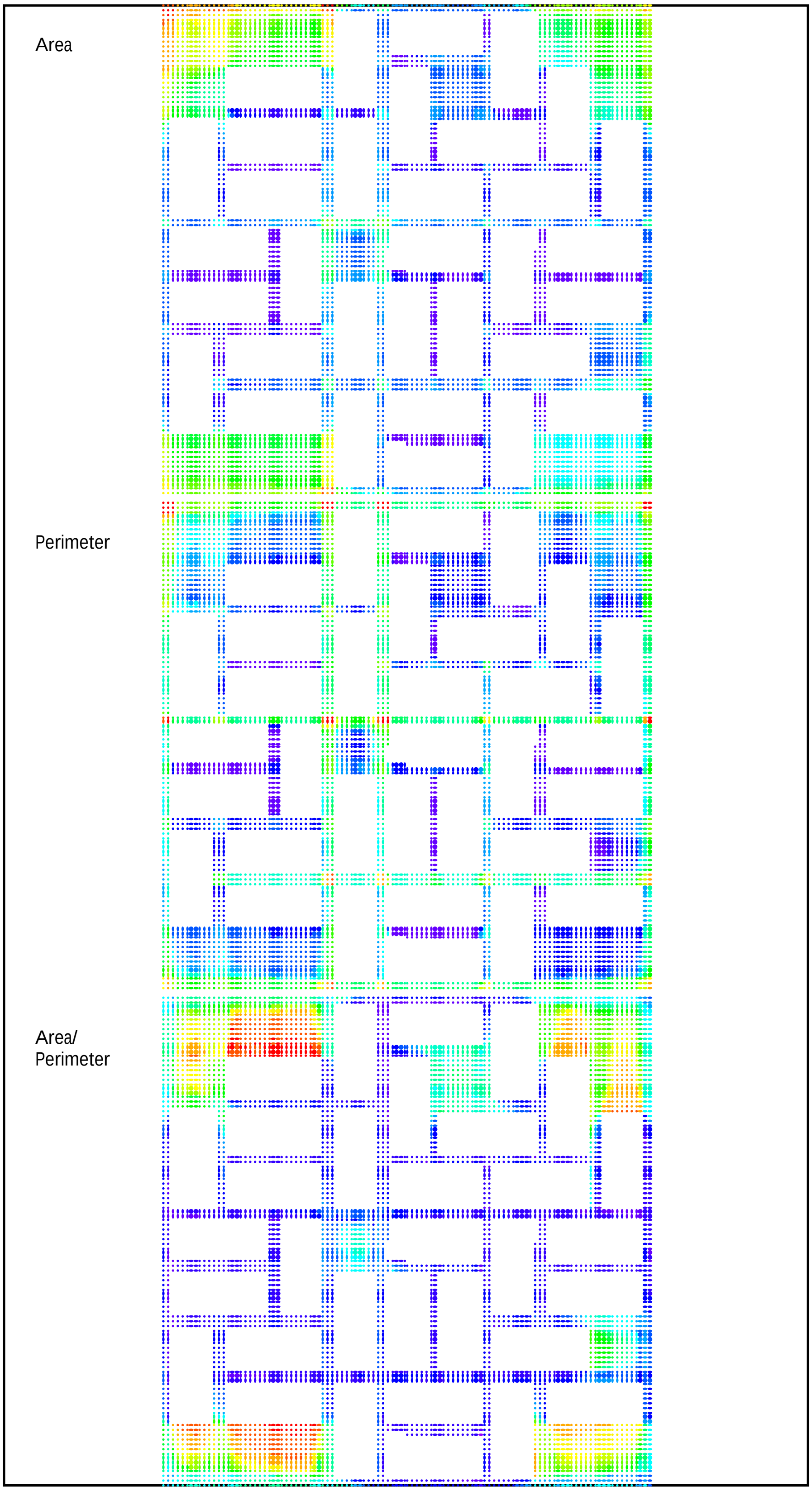


Figure 8.19 Isovist Attribute Maps for World F (Area, Perimeter & A/P)

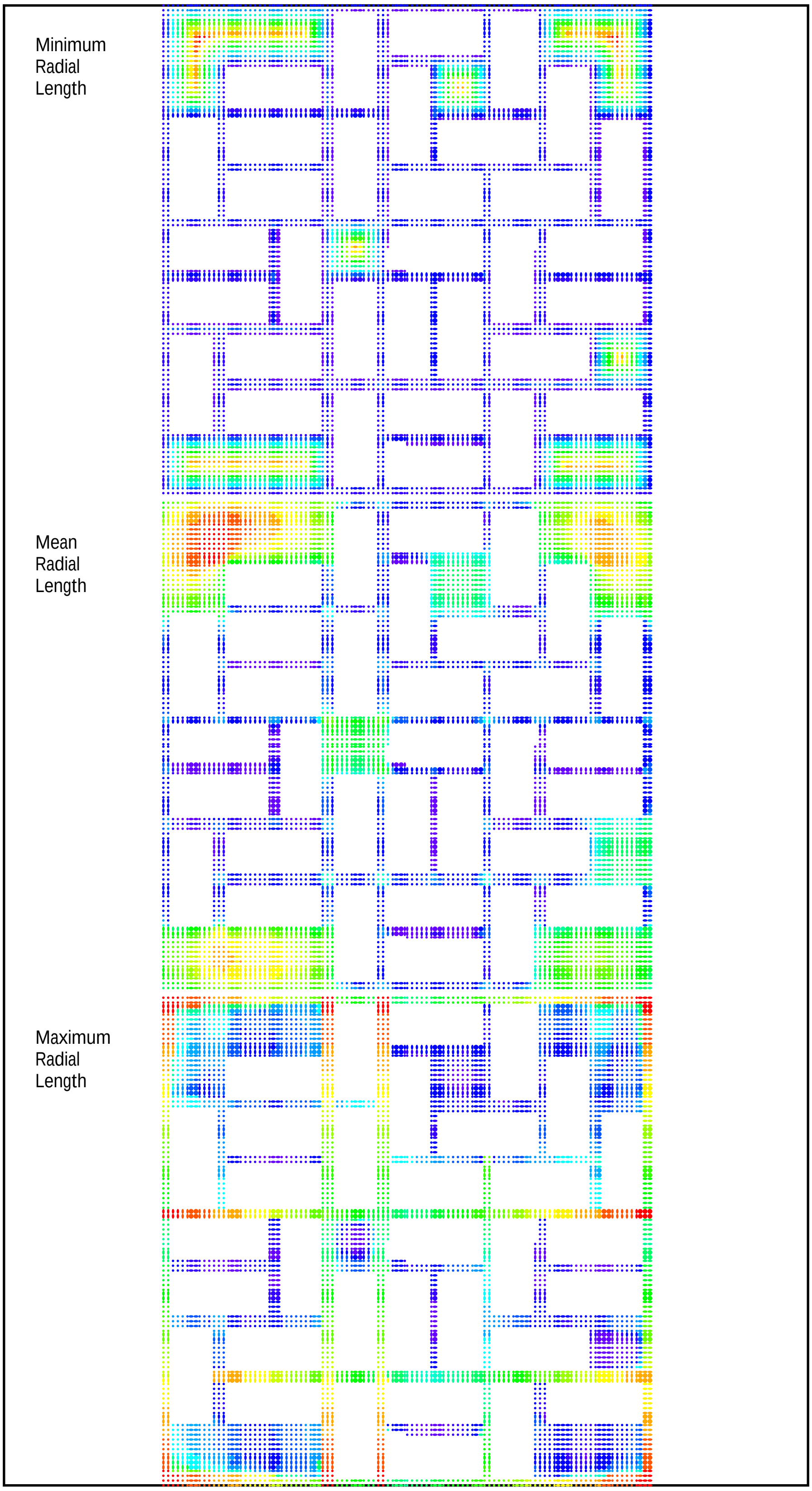


Figure 8.20 Isovist Attribute Maps for World F (Minimum,Mean & Maximum Radial Length)

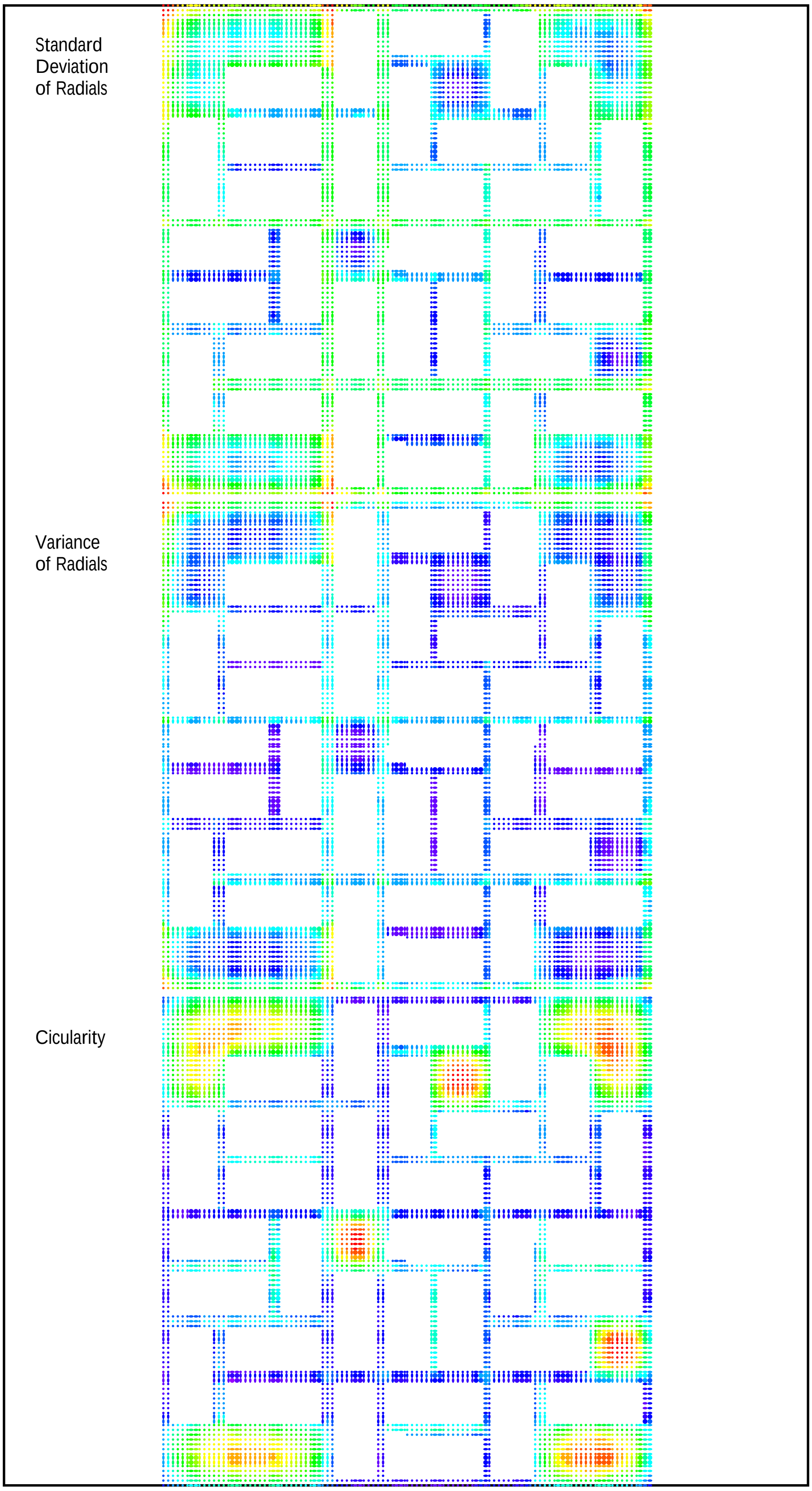


Figure 8.21 Isovist Attribute Maps for World F (Standard Deviation & Skewness of Radials & Circularity)

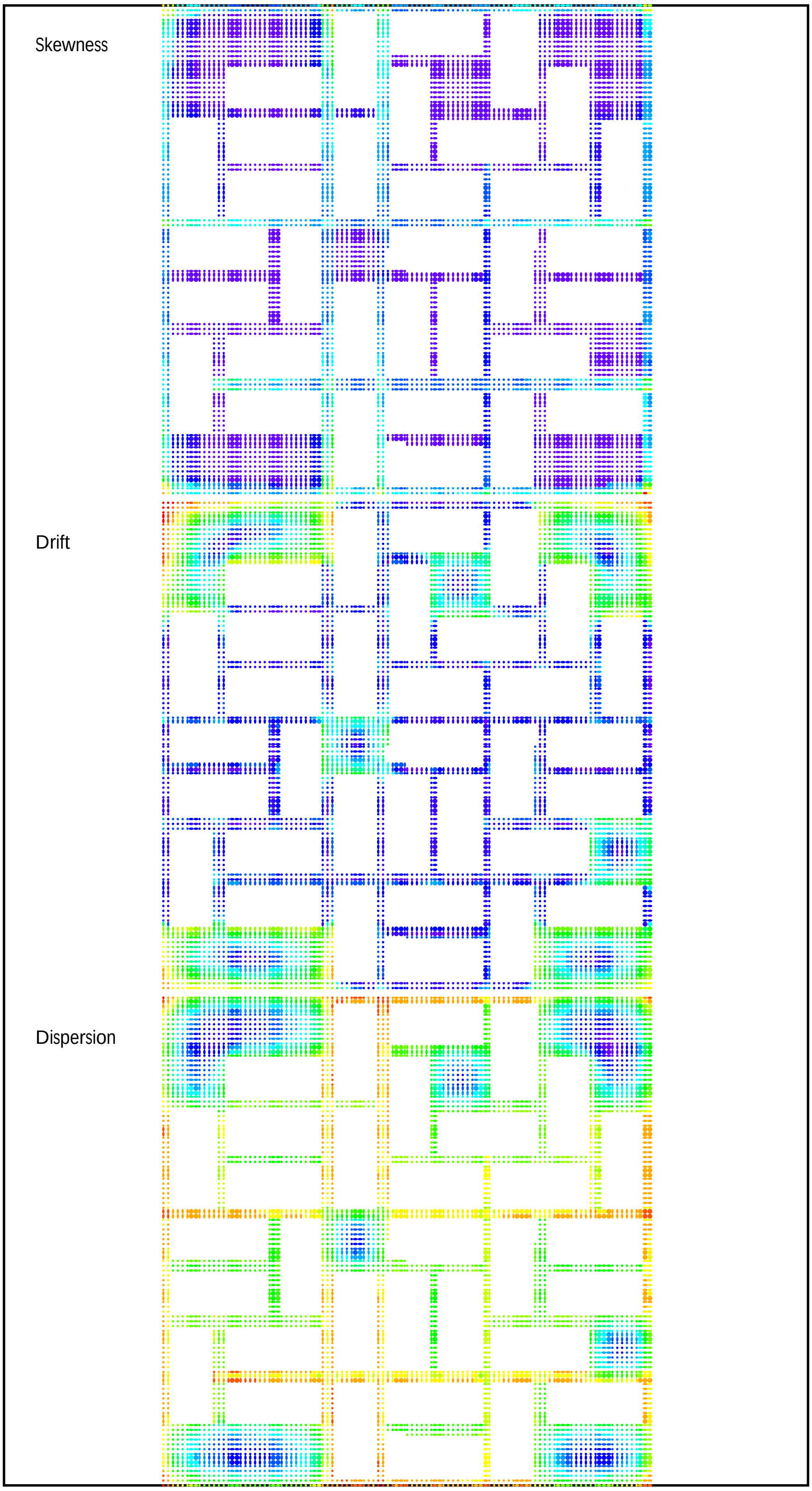


Figure 8.22 Isovist Attribute Maps for World F (Skewness,Drift & Dispersion)

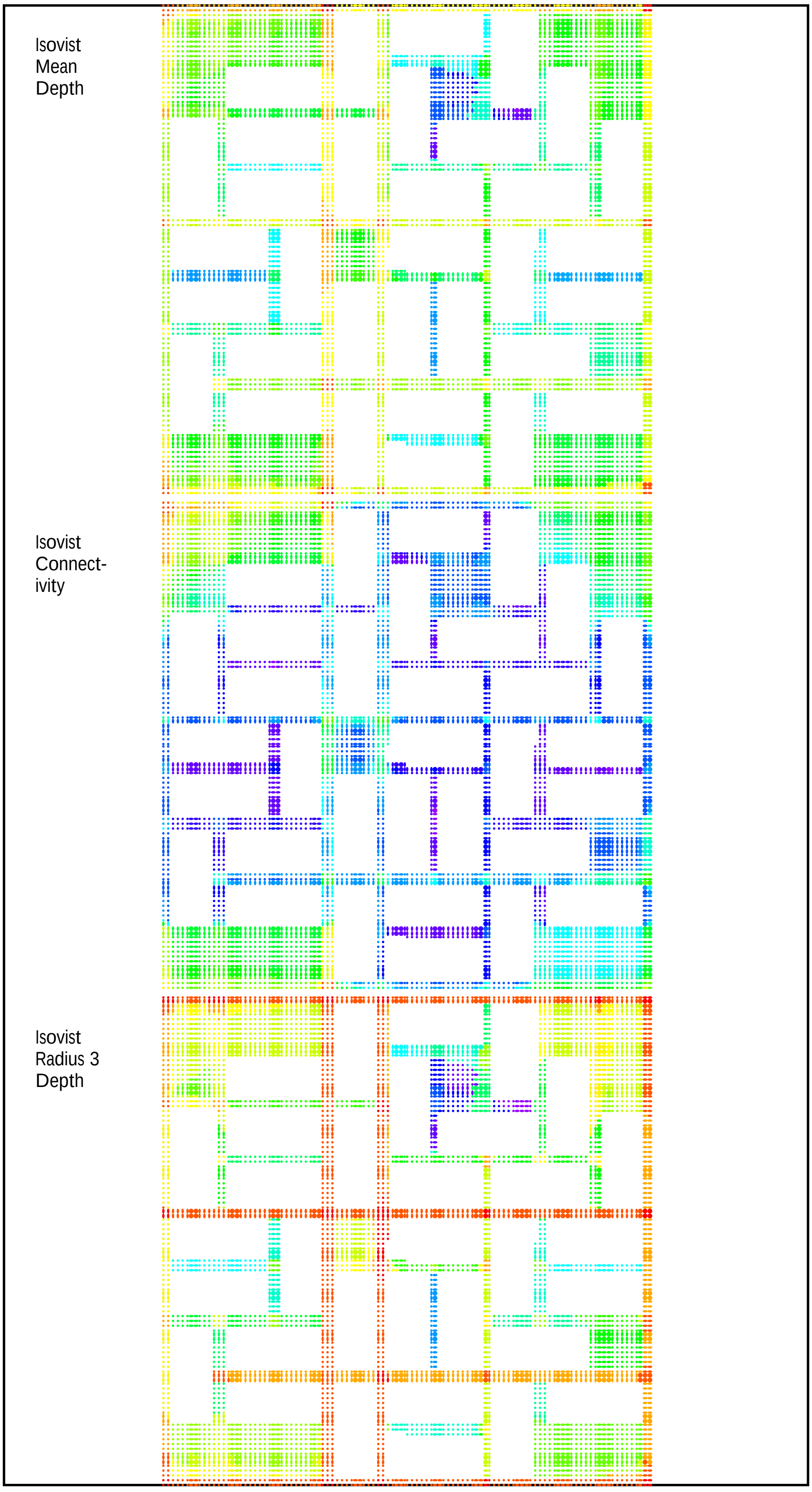


Figure 8.23 Isovist Attribute Maps for World F (Mean Depth,Connectivity & Radius 3 Depth)

Standard Deviation, Variance and Skewness of Radial Lengths

The locations in World F that contain the isovist viewpoints whose radial lengths have the highest standard deviation are those viewpoints in the open spaces at the corners of the worlds. More precisely, the areas of highest isovist radial standard deviation are those locations on the overlap between the open spaces and the longest streets in the world. The areas of least standard deviation or greatest uniformity of radial length are located in the centres of open spaces (particularly the square-shaped spaces) and in several of the smaller side streets.

Circularity, Drift and Dispersion

This world is an extremely good indicator of the types of spaces that have a high value of isovist circularity; the centres of the open spaces in the world appear as vivid ‘hotspots’. It should also be noted that the higher values of circularity do not occur in the larger spaces (those at the corners) but in the spaces that most closely approximate a circle (the perfect ‘squares’ of World F). Dispersion approximates a reciprocal pattern to circularity; locations with a high circularity have a low dispersion and vice versa. The difference between dispersion and circularity (apart from the fact that they are calculated in entirely different ways) is that dispersion is primarily a description of the shape of the isovist polygon. Drift tends towards a minimum value in the centres of spaces, in this sense it is purely a measure of centrality with no reference to shape at all. It is irrelevant whether or not a shape is round or elongated, drift will highlight any points of equilibrium where the viewpoint of the isovist also happens to be located at, or near, its centre of gravity. By these definitions, circularity can be held to combine the essence of both drift and dispersion. Equally drift and dispersion, as measures, can be held to distil different, but nevertheless important qualities of the measure circularity.

Syntactic Measures

In World F, the patterns of mean depth, total depth and connectivity seem less similar (to each other) than in the other worlds. Areas of highest isovist integration occur at the intersections of particularly long streets. Therefore, integration can be held to be identifying key junctions in World F. Two roads, which connect one side of World F to the opposite side, are highly integrated along their entire length. These are the roads that pass through the open square towards the centre of the world. The areas of least integration are found in the shortest side streets. The pattern of highly connected isovists follows a similar pattern to that of integration. However, in the shorter streets, there is less of a range of isovist connectivity values compared to integration values for the same streets.

Pause Point Sampling

The isovist locations with high perimeter values are those with the greatest absolute value of z. The areas with the highest isovist perimeter values are to be found at the junctions of the longest streets in World F. These are areas with extremely high isovist perimeters because the shapes of the isovists at these locations form four-pointed stars with particularly long points. The average length of perimeters for an isovist at these locations are 1789.08m compared to only 980.14m for the whole world. The measure standard deviation of isovist radials appears to be identifying areas of World F, which also have a high perimeter value. Since people appear to be pausing in locations with a large isovist perimeter, then these locations are also locations with a higher than average standard deviation and variance of radial length.

It can also be seen from the table overleaf that subjects are pausing in locations with a much higher than average maximum radial length. People are stopping in World F, where the maximum radial length of their isovist is 454.11m. This is one and a half times longer than the average 294.13m line of sight for all isovists in the world. Subjects also appear to be pausing in locations with particularly high isovist areas and connectivity.

If the isovist attributes dispersion, drift, circularity and minimum radial length are considered as a group of measures, it can be seen that people do not seem to be pausing in the centres of spaces. This is rather at odds with the findings of the other five worlds (also excluding World E) where this pattern is reversed. In essence, subjects in World F are pausing in locations with higher than average dispersion and higher than average isovist 'drift' which indicates that they are pausing in locations which are closer to the edges rather than the centres of spaces. This is reinforced by the fact that these locations also have slightly lower than average values for isovist circularity. The average minimum radial length of the isovist is also slightly lower, 10.28m compared to 11.12m, but this is not a large enough difference to be significant, producing a z value of 1.32. There are two possible explanations for this finding. The first explanation is the same that was applied to the previous world, World E. In the previous section it was hypothesised that since people were travelling at a quicker pace in these two worlds, that their navigational control was impeded and consequently their routes through the world became slightly more erratic. The second explanation for this result is drawn from the spatial layout of the world. World F is characterised by a number of large open spaces. The four largest spaces are at the corners of the world. There would be little advantage to pause in the centre of these corner spaces, since it is clear to any subject that they are standing in the world's corner and hence is neither lost nor disorientated. However, the corner spaces (in which few people paused at all) are sufficiently large in area compared to the rest of the road system, to produce such an effect in statistical sample. In other words, purely by having a world which contained larger than average open spaces, in which few people had any requirement to pause, was enough to alter the distribution of all measures of isovist centrality for the pause point sample.

In keeping with all of the other worlds it can be seen that people are pausing in locations which are more integrated and better connected than the environment as a whole. It can also be noted that subjects are pausing in locations with a higher than average mean radial length (49.89m compared to 43.38m). From figure 8.20 it can be seen that road junctions have a slightly higher than average value of mean radial length and hence this finding supports the hypothesis that subjects are pausing in locations where route choice decisions need to be made.

Measure	Population mean	Sample (PP) mean	Population standard deviation	Sample (PP) standard deviation	Population variance	Sample (PP) variance	"Z" from c. l. t.	"Z" from Z-test
Perimeter	980.14	1789.08	466.95	729.1	218081.92	531584.63	19.52	-12.44
Radial Standard Deviation	43.46	61.89	14.92	19.08	222.59	363.89	13.92	-10.81
Radial Variance	2111.27	4191.71	1380.53	2279.96	1906230.45	5198233.86	16.98	-10.24
Maximum Radius Length	294.13	454.11	165.69	189.94	27458.51	36078.35	10.88	-9.4
Radial Skewness	363530.08	1017598.92	411022.62	792988.25	168972331977	628830359069	17.93	-9.26
Area	13164.61	19575.1	7492.54	8591.29	56149067.31	73810277	9.64	-8.33
Dispersion	0.08	12	22.27	17.07	496	291.33	6.03	-7.71
Area/Perimeter	14.32	11.32	7.8	4.66	60.79	21.73	-4.33	7.01
Drift	13.84	22.43	10.03	14.11	100.52	199.09	9.66	-6.82
Connectivity	367.7	485.62	207.83	221.49	43200.95	49059.01	6.39	-5.94
Radius 3 Total Depth	5409.54	3963.2	3813.05	3043.45	14542181.84	9262577.89	-4.27	5.26
Total Depth	15082.44	14251.44	1892.71	1828.3	3583030.97	3342673.01	-4.95	5.06
Mean Depth	2.92	2.76	0.37	0.35	0.13	0.13	-4.95	4.97
Mean Radius	43.38	49.89	19.84	15.66	393.77	245.14	3.7	-4.6
Circularity	0.49	0.43	0.22	0.13	0.05	0.02	-2.99	4.53
Mean Depth Radius 3	4	4	0.14	0	0.02	0	0.38	-2.36
Absolute Dispersion	18.71	17.01	12.08	12.03	145.86	144.69	-1.58	1.57
Minimum Radius Length	11.12	10.28	11.03	7.01	121.7	49.12	-0.86	1.32

Table 8.8 Tabulated Population and Sample Data from World F

World G

Area, Perimeter and Area/Perimeter

Without question, the locations with highest values of isovist area are those isovist viewpoints situated in the keyhole-shaped space to the left of the centre of the world, the area known as Thornhill Square. The isovists with the greatest area in World G occur at the intersection of the streets that lead into and pass through this square. Other large-area isovists are found at the junctions of other streets in this simulation world. This pattern precisely mirrors the pattern of high isovist perimeter values. The distributions of the measure area/perimeter ratio are uniformly low throughout the street network of Barnsbury and only Thornhill Square yields any particularly high values. Note the manner in which these higher values increase towards the edges of the square yet are disrupted by the streets that lead from the square.

Minimum, Mean and Maximum Radial Length

The distribution of minimum radial length highlights the three open squares[11] in Barnsbury. The streets, being of equal width, all have a relatively uniform value of minimum radial length. In World G, the longest lines of sight (as identified by the isovist attribute maximum radial length) occur at the ends of the longest, straightest roads in the world. The areas of highest maximum radial length are found at the ends of Caledonian Road (to the left of the world, on plan) and at either end of Offord Road (across the top of the world) and finally at the endpoints of Hemingford Road (running vertically through the middle of the world). Conversely, the areas of least maximum radial length are at the ends of cul-de-sac streets (dead-ends).

Standard Deviation, Variance and Skewness of Radial Lengths

The areas of greatest standard deviation of radial length, which can also be regarded as being a measure of the 'spikiness' of an isovist, are the isovist locations at the junctions of particularly long roads.

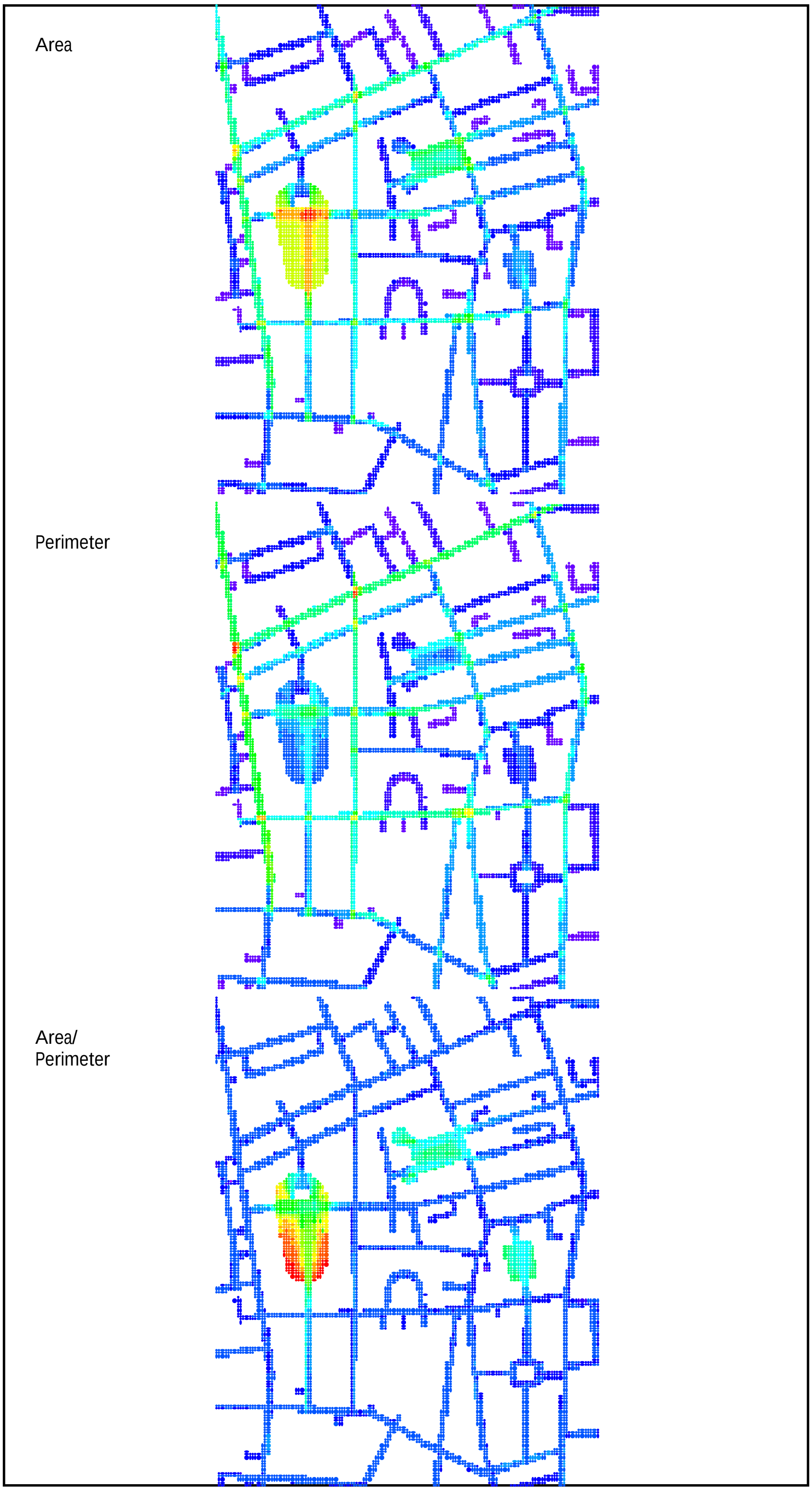


Figure 8.24 Isovist Attribute Maps for World G (Area, Perimeter & A/P)

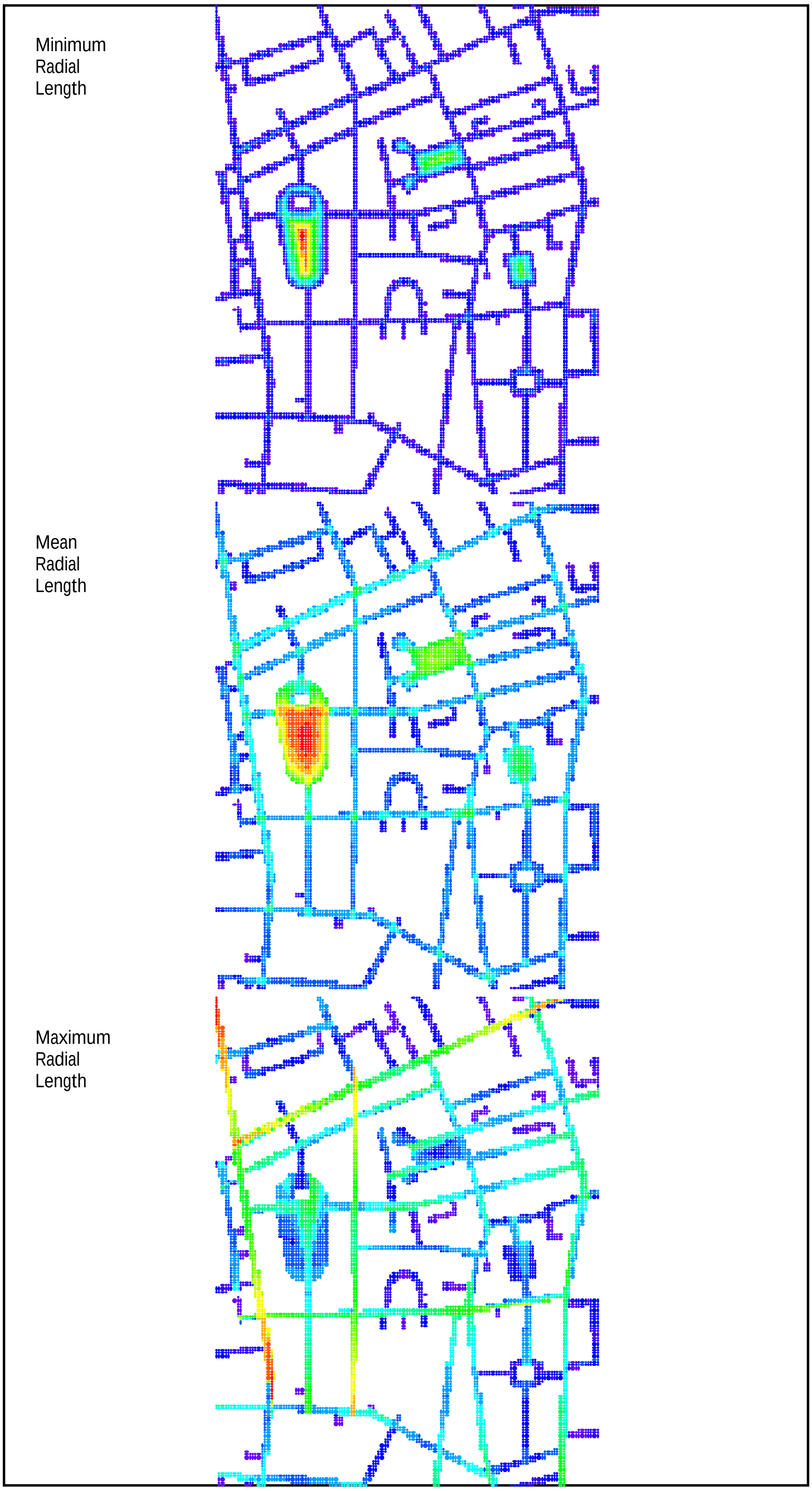


Figure 8.25 Isovist Attribute Maps for World G (Minimum,Mean & Maximum Radial Length)

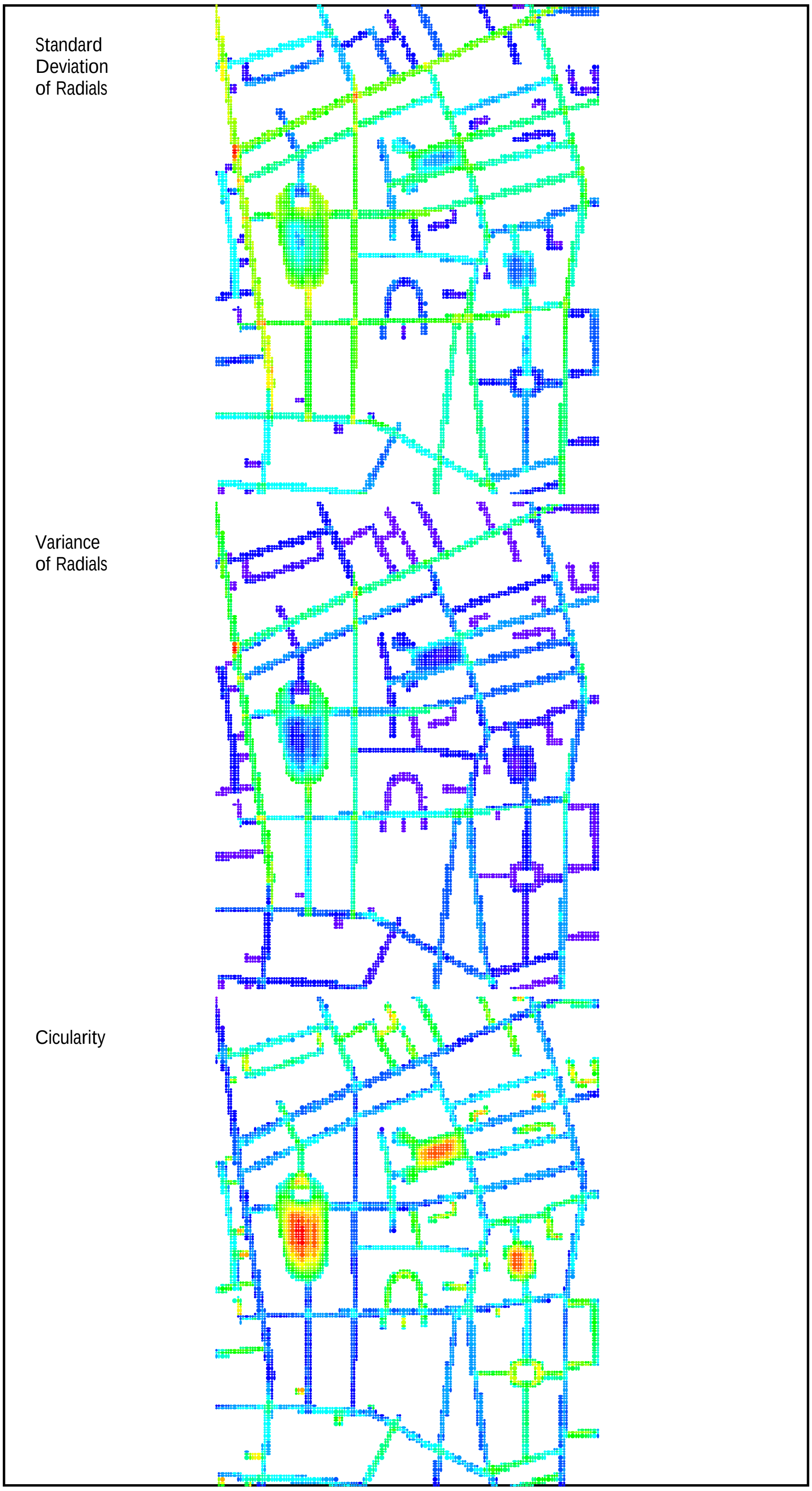


Figure 8.26 Isovist Attribute Maps for World G (Standard Deviation & Variance of Radials & Circularity)

The area with the greatest standard deviation of radial lengths is the junction of Caledonian Road (to the left of the world, on plan) and Offord Road (across the top of the world, on plan). All of the primary roads in this simulation have a higher than average value of standard deviation. The difference between the primary and secondary roads in Barnsbury is emphasised by the visualisations of the isovist measures variance and skewness; the primary roads appear as a prominent light blue against the dark purple of the side roads and cul-de-sacs. The areas of highest variance appear as red or orange patches at the intersections of the major, light blue, roads.

Circularity, Drift and Dispersion

The isovist analysis of Barnsbury illustrates the types of urban spaces that are highlighted by the isovist measure circularity. Circularity reaches maximum values in locations where the shape of the isovist approximates a circle *and* the viewpoint of the isovist is close to the centre of the isovist. From the perspective of an observer, the environment would appear to be equally distributed in all directions around that point. The areas in the world with the lowest values of circularity are the longer, straighter, narrower streets. Therefore, the area with the highest level of circularity in World G is the centre of the keyhole-shaped ‘square’. This is also the area with the lowest values of dispersion (the distribution of dispersion is approximately the inverse of circularity). The visual representation of drift, for World G, bears a strong resemblance to the measure minimum radial length. This is because most of the world consists of roads of similar width and therefore the only high values of drift occur in open spaces. Note however, the square in the bottom, left-most corner of the world, a square with a visually occluding block in its centre - the values of least drift cut across the corners of this square forming a diagonal route, highly reminiscent of the axial break-up of this area.

Syntactic Measures

The Space Syntax measures reveal slightly different patterns for connectivity and integration. The distribution of high global integration for World G is quite fascinating. The most integrated areas are the junctions of the five longest and straightest roads in the system. The road segments[12] are also quite highly integrated; the most integrated roads are Caledonian Road, Richmond Avenue and Hemingford Road. This distribution of values is similar to the pattern of connectivity (which of course is also a good approximation to isovist area). The representation of the isovist measure connectivity emphasises more integrated roads whilst making the segregated roads appear visually prominent through their dark blue and purple colours. The areas with the most visually connected isovists are the locations at the junctions of the longest and straightest roads in the network.

Pause Point Sampling

The essential isovist attributes that appear to be influencing the locations in which people are choosing to pause are the Space Syntax measures. Without exception, subjects are pausing in locations with significantly higher than average isovist integration values or lower than average mean depth (both locally and globally) and in areas that are far better connected than the average for the world. As world F is the only simulation of an *urban* environment used for this set of experiments then the strong

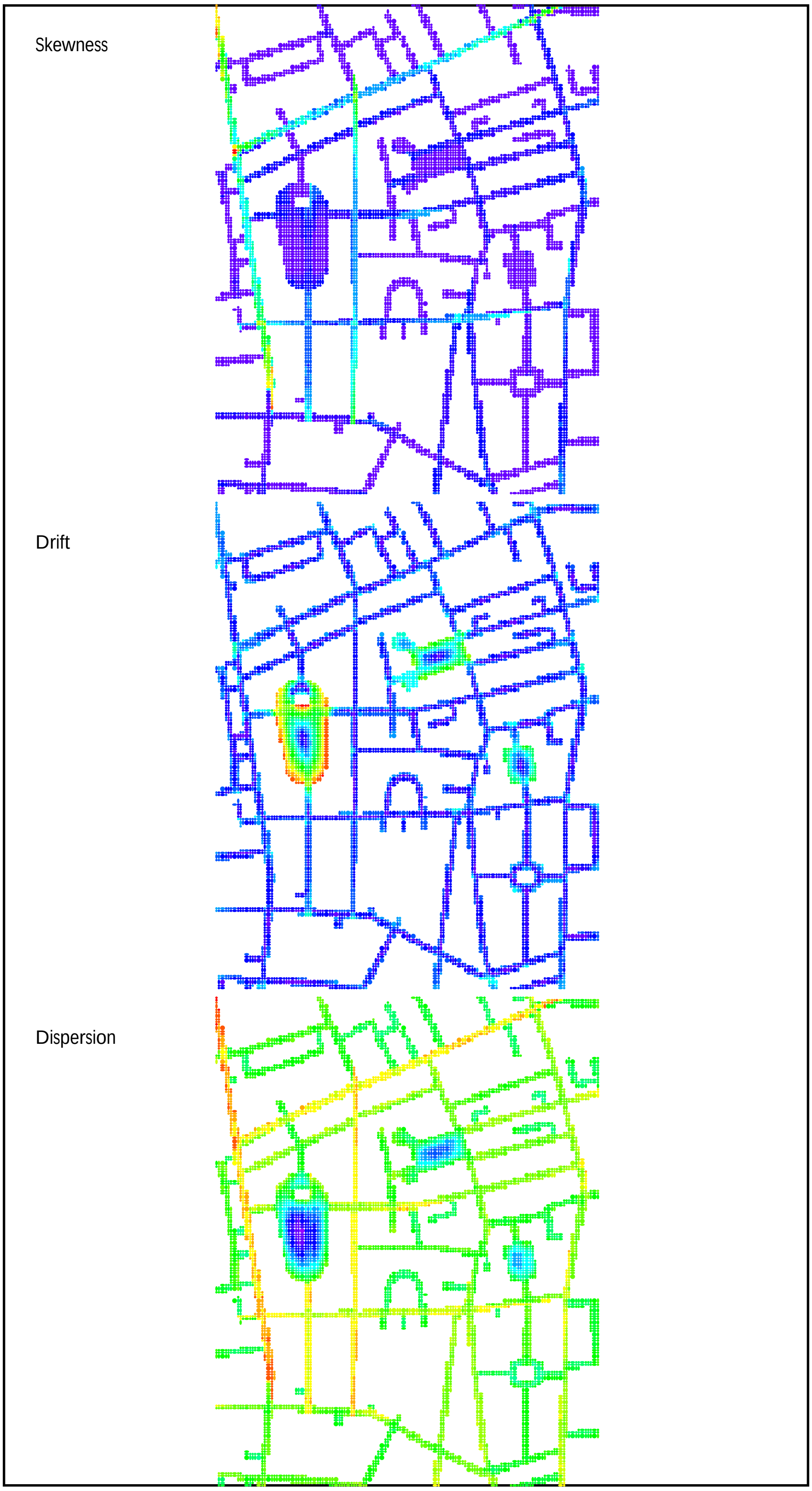


Figure 8.27 Isovist Attribute Maps for World G (Skewness,Drift & Dispersion)

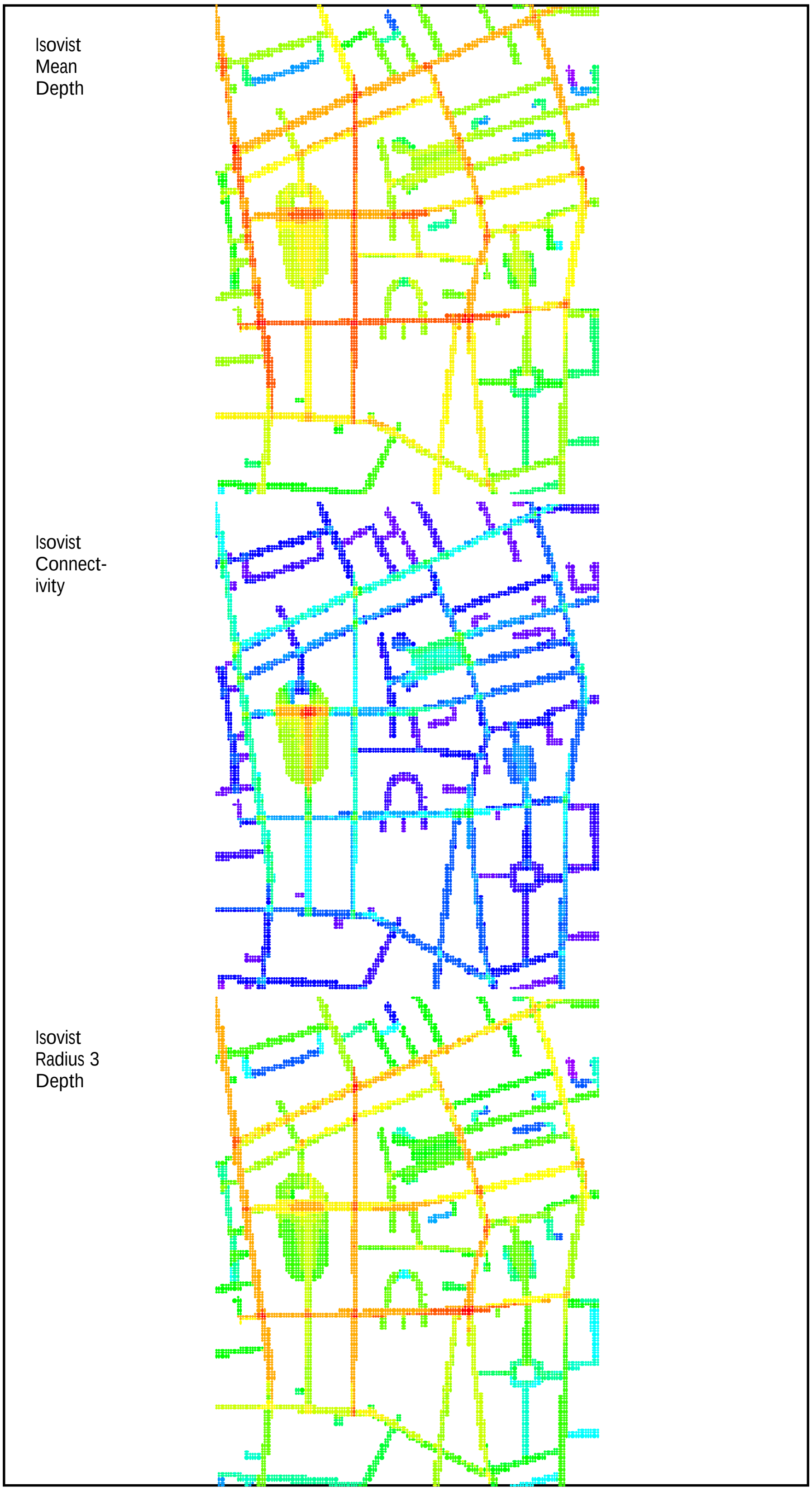


Figure 8.28 Isovist Attribute Maps for World G (Mean Depth,Connectivity & Radius 3 Depth)

effect of this particular family of measures is all the more significant.

The locations where subjects are pausing in this world also have much higher than average values of mean radial length. The value for the pause point sample is 25.04m whereas the value for the population of all possible grid isovists is only 17.23m. Since mean radial length appears to be a good indicator of junction location, then this suggests that people may be pausing at road junctions as well as other open spaces (such as squares). Subjects are also pausing in locations with a high isovist perimeter value (a value of 795.10m compared to 548.37m for the rest of the world). In World G, the areas with extremely large isovist perimeters are those at the intersections of the major roads in the area. The fact that people are stopping in locations with a particularly high isovist perimeter values supports previous statements that subjects are pausing at or near road junctions. In addition to this, note the higher than average values for isovist radial standard deviation, variance and skewness which also support this hypothesis.

People appear to be pausing in locations that are far from any occluding surfaces, a distance of, on average, 7.58m compared to 3.54m for the rest of the environment. This is reflected in the higher than average values of isovist circularity for the pause point sample. This finding is in accordance with the results of worlds A-D (with the exception of worlds E and F). This overall result supports the hypothesis that people are pausing strategically in this world, as in the other six worlds. In essence, people are pausing in locations with longer than average lines of sight, greater isovist area/connectivity, more integrated in terms of the system as a whole and further from any occluding edges. These are all locations that afford the greatest visual information about an environment; people are not only pausing strategically, but efficiently too.

Measure	Population mean	Sample (PP) mean	Population standard deviation	Sample (PP) standard deviation	Population variance	Sample (PP) variance	“Z” from c. l. t.	“Z” from Z-test
Total Depth	22378.58	20144.43	3662.58	2340.57	13416751.07	5478270.38	-7.57	11.48
Mean Depth	3.82	3.44	0.63	0.4	0.39	0.16	-7.57	11.47
Radius 3 Total Depth	16217.52	12239.18	6257.51	4425.76	39163090.11	19587352.61	-7.89	10.87
Mean Radius	17.23	25.04	8.28	10.25	68.59	105.16	11.7	-9.37
Mean Depth Radius 3	4.13	4.02	0.39	0.14	0.15	0.02	-3.58	9.05
Area	2801.65	4496.18	2026.75	2541.19	4108422.5	6457670.68	10.38	-8.21
Perimeter	548.37	795.1	310.58	381.33	96475.89	145409.11	9.86	-7.96
Connectivity	175.51	282.21	131.04	170.58	17174.57	29099.01	10.11	-7.7
Minimum Radius Length	3.54	7.58	3.94	6.55	15.54	42.84	12.72	-7.62
Circularity	0.4	0.49	0.16	0.18	0.03	0.03	7.13	-6.59
Radial Standard Deviation	22.62	26.41	8.96	9.26	80.34	85.74	5.25	-5.02
Radial Variance	591.79	782.65	421.51	483.65	177701.09	233918.8	5.62	-4.85
Dispersion	5.39	1.37	8.99	11.15	80.86	124.22	-5.54	4.43
Area/Perimeter	5.08	5.8	2.76	2.78	7.6	7.75	3.24	-3.17
Maximum Radius Length	170.52	190.26	103.32	95.16	10676.73	9054.78	2.37	-2.53
Radial Skewness	76648.54	90724.63	102248.94	110269.02	10456630055.7	12159257055.9	1.71	-1.57
Drift	4.58	4.09	3.85	4.23	14.79	17.86	-1.58	1.42
Absolute Dispersion	8.45	9.17	6.2	6.45	38.49	41.55	1.43	-1.36

Table 8.9 Tabulated Population and Sample Data from World G

Conclusion

This chapter concludes that subjects do not appear to be pausing randomly in these virtual environments. People are pausing in locations offering strategic visual properties, locations that afford unusually long lines of sight and large isovist areas. These are also the kinds of locations where the isovists are highly integrated as well as highly connected in the system. Lastly, it seems that people are pausing in locations far from any occluding surfaces such as building edges (which would limit available environmental information). It may be summarised that the subjects are being exceedingly strategic in terms of where they stop to survey the worlds. They pause only in locations offering maximum visual, local/global information, reducing the necessity to pause more frequently. People's navigational tactics can therefore be seen to be both strategic and maximally efficient.

Differences can be seen to occur between subject's behaviour in distinct worlds. The most significant difference is found between subjects in Worlds C and D and Worlds E and F. In these pairs of worlds, one environment is more intelligible than the other. In the intelligible environments, the syntactic measures of the isovists can be seen to be influencing where people are pausing; they are pausing in locations that are highly integrated and well connected. However, in the unintelligible environments (most markedly, World D), the syntactic measures of the isovists appear to exert far less influence on stopping behaviour. This suggests that since these worlds are examples of unintelligible environments, these measures are relatively uninformative; there is only a weak correlation between local and global measures in these worlds. It is, therefore, appropriate that these syntactic measures are not being used by the subjects to navigate since they are far less useful than the same measures would be in an intelligible environment. This difference in subjects' behaviour, found in these pairs of worlds, is a significant finding of this chapter.

The research question of this thesis asked what kinds of small-scale actions are being made by subjects such that their overall patterns of movement resemble aggregate pedestrian flows observed in real-world environments. In earlier chapters, it was demonstrated that similarities were evident in the types of route-choice decisions made by subjects at junctions. In this chapter, it was then hypothesised that the kinds of locations in which people paused momentarily were important and could potentially provide additional information about the route-choice decision-making process. It was further hypothesised that subjects were more likely to pause if a route choice decision needed to be made and that the solution was not immediately clear. The results of this chapter appear to suggest that the shape of the space occupied by a subject may be important to the decision making process. This chapter concludes that subjects are pausing to scrutinise the environment in locations that afford most information and consequently that this is the key information contributing to the route-choice decisions made during a journey.

Key Points

- Certain geometric properties of individual isovists correlate to isovist syntax properties. I.e. it is possible to make inferences about global information from only local measures
- People are not pausing randomly in the world with regard to isovist properties. Subjects can be seen to be pausing in locations which offer

strategic visual properties; locations with long lines of sight, large isovist areas, integrated within the system and far away from any occluding surfaces such as building edges.

- Subjects may exhibit different behaviour in intelligible environments compared to unintelligible ones.

Notes

1 OmniVista is an isovist analysis programme for the Apple Macintosh computer co-developed by Ruth Conroy and Nick 'Sheep' Dalton specifically for this doctoral thesis.

2 The grid spacing is predetermined in the application OmniVista and can be set to any integer value. However, the finer the grid resolution the longer the processing time; doubling the number of generating points also doubles the time taken to process the environment.

3 Lamina n. (pl. -nae) thin plate or scale. Laminar adj. [Latin].

4 The type of analysis used in the programme Meanda, Dalton, N. M. (2000). Meanda. London, Architectural Association., does use a fractional rather than integer method of integration and is unusual in this approach.

5 This matrix was created by taking the geometric and syntactic values for an array of isovist locations covering all navigable space in World C.

6 The reason why two distinct statistical tests were used was to be able to verify the results of one test through the application of a second test.

7 Note that drift lines (lines connecting an isovist's viewpoint to its centre of gravity) are always entirely contained within the perimeter of the isovist and that the value of drift must always be positive.

8 Verbal conversations with Major and Hillier about the geometrically-derived urban grids of the United States have discussed why people are inclined to traverse grids diagonally. Major's suggestion is that people will take small-scale short cuts across spaces, which incrementally constitute a reduction in distance when cumulated over the entire journey.

9 Benedikt makes a differentiation between minimum path and sufficient path, this probably is not a minimum path, but could be termed a sufficient path.)

10 See Chapter 4 for a definition of intelligibility of environments.

11 Two of these three squares were also used as wayfinding goals for the subjects' navigation task and that the one square which was not a goal was commonly misidentified as one.

12 A road segment is the section of a road between adjacent junctions.

Chapter Nine:
Discussion and Conclusion

Abstract

This chapter takes the conclusions of Chapters 3 through to 8 and combines their individual conclusions whilst discussing their implications in a wider academic and application-based context. It concludes with a statement of future research directions that could arise from the work forming this thesis.

Without question, the primary finding of this thesis is that it is possible to use virtual environments to gather data about people's likely behaviour in the real world. In essence this data can be regarded as being 'free data' which is inherent to all virtual world simulations. All systems for navigating through virtual environments use this data to continually update the visualisation of the world, be it the world as represented through a sophisticated headset or as displayed upon a standard computer monitor. This data consists of: a subject's location within a scene, their orientation (which way they are facing), a description of which objects can be seen by the subject (which surfaces are occluding other surfaces and which are completely hidden) and finally the commands given by the user to move around and re-orient themselves within the environment. Without such data, it would be impossible to navigate a three-dimensional virtual world (although many users are unaware that this data exists), since it is kept 'behind the scenes' and hence can be regarded as transparent. It so happens, though, that this is *also* the very same data that can be used to research the behaviour of people within an environment. This is not a case of generating data since the data already exists. The methodological challenge is to find a way to tap into and to retrieve this data for further analysis.

Not only can a subject's behaviour be sampled quite rapidly (in the case of these experiments at a rate of ten times every second), this rate exceeds that at which we can easily observe similar behaviour in the real world. This shows one advantage of using virtual environments for this kind of research: the ease at which navigational data can be collected exceeds any real world equivalent. Not only can data be sampled more rapidly, but also more accurately.

The real-world observational data that was used in this thesis was gathered by hand; although we are beginning to see the use of automated techniques for investigating people's behaviour in the real word, such as the use of active badges, video capture/analysis, infrared beams and pressure pads, they are still techniques that are in their early stages of use. The majority of observations are still done by hand. The analogy that can be applied here is that the difference between real-world observations and virtual navigational data is akin to turning up the focus on a microscope; the resolution of the data is far finer for virtual world data, with less 'noise'. If it can be demonstrated that people's patterns of navigation in virtual worlds are analogous to real-world movement, then the use of virtual worlds to investigate navigation and other behaviour should grow in popularity.

Another advantage to the use of virtual environments to investigate patterns of navigation is the range of world types that can be used. The worlds that can be used in such experiments can range from simulations of real buildings or urban environments to entirely fictitious, theoretical worlds. For this reason it would be possible to design purely theoretical worlds which tested one particular spatial variable which a researcher was investigating, and hence to gauge the effect of that particular variable upon movement. If the essence of the scientific method is to reduce and isolate the possible number of variables, then this can be done using theoretic virtual environments in a manner that would be nearly impossible in the real world. The other advantage of using virtual worlds is reduction of noise in the data. Not only is this noise reduced through the automated method of the data collection but, the design of the worlds themselves can eliminate noise. Users can navigate through 'pure', 'exact' environments that are completely different to the visually complex environment that we inhabit daily.

It should be mentioned that an important fact concerning the potential future use of such techniques was that, in the experiments forming part of this thesis, subjects found it extremely easy to navigate through these environments immersively. The usually steep learning curve required to learn how to move through these worlds was in fact very shallow, making the technology ideal for such experiments. It meant that subjects could be used from all occupations, and did not need to be familiar with this type of technology. Ultimately this is an advantage since it allows for a more representative sample population. At the moment, with current technology it seems that it is far easier to navigate through an environment immersively than it is to navigate on a desktop.

The thesis begins by addressing what was probably its predominant question. The question that was first posed in Chapter 1, was whether the research findings obtained in virtual worlds could be held to be indicative of real world behaviours. The reason why this question is so essential to the thesis concerns future applications of the research. If these two patterns of movement can be regarded as being analogous then it may be inferred that all the findings from the rest of the thesis may be applied to real world pedestrian movement too. Without this correlation, the results may be intrinsically interesting, but the applications are extremely limited. The fact that this thesis held the answer to this question to be so important was also interesting since many researchers in this field assumed that this relationship could be taken for granted.

After comparing the movement patterns for the Tate Gallery it would appear that people move through virtual worlds in a manner that is analogous to the way in which we navigate in real environments. The correlation of the two sets of data for the Tate Gallery was found to be particularly good. Since the virtual simulation of the Tate Gallery was only a spatial model and contained no art or other people, such a high correlation was all the more surprising. This result implies that the building (and spaces) plays a far greater role in determining where people walk than any other single factor.

Other factors that effect the correlation of the data are the physical constraints of the worlds. It was assumed, as one of the basic requirements of this thesis, that the physical constraints of the virtual world should emulate real world constraints in order for this to be used as a viable research tool. Navigation in virtual environments can be quite different from the real world. In virtual environments, it may be possible to fly, to pass through walls or even to jump instantly from one location to another. For this technology to serve as a useful research environment these abilities need to be curtailed, such that the experience is as close to walking in the real world. The good correlation yielded by the Tate Gallery data supports this decision to create a virtual environment that also simulated solidity and gravity.

Having determined that we *can* learn from virtual behaviour, how people are likely to act in the real world, the thesis continued by conducting a series of wayfinding experiments in six, distinct virtual worlds. It became clear at the end of Chapter 4 (when all of the movement paths for all worlds were presented together), that even from this simplest of visualisations, i.e. prior to any additional analysis, that route path data can be extremely informative with regard to how people were using space. It was concluded at the end of Chapter 4, that people appeared to be moving through space in a manner consistent with the chapter's accompanying Space Syntax analyses. Observations that people appeared to be moving syntactically were made based on the relative locations of the most and least popular routes.

It became evident that a measure of route popularity could serve as a useful tool to analyse the subjects' route paths. It was found that it was possible to compare routes by means of a cumulative measure of the spaces through which a subject had passed. This was achieved by representing each space in an environment by an ASCII text character and then representing any route through an environment as an ASCII string. Once a route could be represented as a string, it was possible to perform string matching analysis on any two routes to determine now similar they were to one another.

String matching analysis is a common method that has many varied applications. The first part of using this technique involved nothing more than applying an existing technique to novel problem. The second stage that was employed could be seen as an innovative modification of string matching techniques. Instead of merely comparing pairs of routes to determine how similar they were, it was decided to compare each route to every other route in the sample. Eventually a single number, termed the MNLD (mean, normalised Levenshtein distance) value could be calculated for each route. This number would indicate how similar that route was to every other route in the sample. The routes that were most similar to all other routes could then be regarded as being the most representative routes of the sample. The routes that were most dissimilar could be held to be the most idiosyncratic of all the routes.

Once again, a similar method to the technique for visualising routes by their angularity value could also be applied to visualising routes by this new similarity measure. When visualising routes by their mean angularity, the values of the sample of routes were matched to a colour spectrum, the straightest routes being coloured red and the most undulating routes coloured blue. Since every route could also now be assigned a similarity measure too, the most representative routes of the sample could be coloured red, whilst the more idiosyncratic routes could be shaded blue. These two methods of route visualisation could be usefully applied in conjunction. In this manner it could be determined at a glance whether the most popular routes were the straightest (as is the case) and that the least popular routes were the most meandering.

It was noted that the most popular routes in a sample were frequently the 'straightest'. This observation led naturally to question what kinds of route choice decisions were being made, such that they produced this phenomenon. The most obvious type of location to use in this attempt to analyse subject's decisions were road junctions, as these are locations where a route choice decision *has* to be made. The paths made by all subjects through one world were broken down to the level of their constituent road segments and junctions. The decisions made by each subject at each junction were painstakingly recorded. It was determined that any single route through an environment could be assigned a score based upon the culmination of the decisions taken at each junction where it was necessary for the subject to make a route choice decision.

The method of assigning a score to a route is achieved by noting, at each junction along a route, the range of possible route choices available and comparing these to the choices actually made by the subject. By noting the choice made at each junction, the journey of a subject could be expressed solely in terms of the decisions made by the subject. Equally, all the decisions made by the subject could be summed to produce a cumulative score. If the average decision (in degrees) made by a subject (for a single journey) is plotted alongside the maximum, mean and average angles at each junction (also averaged over the route), then the choices made by subjects appear to lie closer to the maximum angles than to either the average or the minimum. It was also noted that the variance and standard deviation of the 'angular difference' between the chosen angle and the available angles for all 306 junction-decisions in this sample is less for the angular difference between the chosen angle and the maximum angles than for the mean and minimum angles. In other words, it appears that subjects are choosing the straightest possible routes as opposed to the more meandering or undulating routes. This is a particularly significant result that supports hypotheses made by Hillier stating that people tend to follow the longest line of sight that approximates their heading. This finding would certainly begin to suggest the type of micro-scale decisions necessary to produce the aggregate patterns of pedestrian movement observed by Space Syntax researchers, over the last twenty years at UCL, that correlate so well with axial analysis. By following the longest lines of sight, a subject is both deviating as little as possible and behaving axially.

One interpretation of why people should wish to move in as straight a line as possible concerns human memory and complexity. It could be suggested that the act of deviating as little as possible serves to reduce complexity in an otherwise extremely complex environment. There is a well-documented phenomenon termed route angularity, which is mentioned in the following papers (Tolman 1938; Sadalla and Montello 1989; Montello 1991). Route angularity is the effect of judging a route that contains many changes of direction to be longer than a straighter route of identical length. This might also be linked to the 'magic number' in psychology. This was a finding by Miller in (Miller 1956) that stated that people found it easy to remember (short term) up to seven items, give or take two. These two findings begin to suggest why people unconsciously attempt to steer a straight path. It would be an interesting area of future research to investigate the effects of route angularity using virtual worlds, and in particular to determine whether or not 'seven, plus or minus two' junctions or changes of direction were significant.

The overall conclusion of this section of the thesis was that the choices made by subjects at junctions appeared not to be randomly made. This finding can be linked to the previous conclusion formed by analysing the isovist properties of pause point locations. Since it has already been suggested that people are not pausing randomly (in terms of location), but strategically. It can then be further suggested that there is also a pattern to the kinds of decisions that people are making as well. Note, however, that both of these findings appear to be the result of unconscious behaviour. In the questionnaires given to the subjects to complete after participating in the experiments, there was a question asking whether subjects had used any specific strategy to aid their wayfinding task. None of the answers given could give rise to the results described above.

In an attempt to further analyse the results of the route angularity finding, the absolute angle selected at any node was plotted against the maximum angle of incidence for each node. Regression analysis was performed and the resultant value for r-squared was 0.342. This implies that factors other than angle of incidence contribute to route choice decisions. It is suggested that the other factor determining route choice decisions is approximate direction or heading. Namely, that subject will choose the greatest angle of incidence at a junction on condition that it is in the approximate direction that they are heading. Once again, this entirely supports the theories put forward by Hillier.

Finally, as a way of concluding this section of work, a method was proposed to visualise the results of the route angularity analysis. Since the cumulative value of all decisions made along a route could be calculated it was also possible to determine the average decision made at any junction. Routes could then be ranked in order of the average angle turned through during the whole journey and subsequently colour-coded accordingly. This technique appeared to provide a valuable method of visualisation, supporting an intuitive estimation of a route's 'straightness'. Whilst still considering micro-scale behaviours along routes, a representation of the changing visual field along a route is presented. This representation is termed the route vision profile.

The thesis then shifts its emphasis from entire routes (linear behaviours) to smaller-scale actions taking place at instance along a route (positional behaviours). One kind of micro-scale behaviour that it was possible to calculate from the raw data, was the location in the world where people were pausing. This could be represented as a 'point' on plan, superimposed upon the original route path. The first conclusion to be drawn from this method of visualisation was that people appeared to be pausing at or in close proximity to road junctions. Another way of describing this phenomenon was that people appeared to be pausing in locations where a route choice decision needed to be made. However, people were not pausing at every junction that they encountered, there appeared to be only a few locations where they paused. One interpretation of this was that subjects appeared to be pausing at locations where a route choice decision needed to be made, but where the correct or appropriate choice was not immediately obvious. Where the decision *was* immediately clear, the subjects appeared not to pause or hesitate at all, but simply continued with their journey. It was only where the subjects were unclear of the choice that they needed to make that they paused to look around and to scrutinise the environment to aid them in their decision making. Another conclusion arising from this section of the thesis was that the combination of direction of gaze and pause point analysis appeared to be the most useful method of combining the data available in a graphical form. Once this data had been combined, it was not only easy to determine where a subject had travelled, but where they had stopped for long periods of time and while they had been stationary, in which direction they had been looking in order to inform their navigational decisions. The most intriguing aspect of this extremely simple way of visualising the data, was the way in which it was hard not to attempt to interpret and recreate the 'story' of an individual journey.

After the calculation and visualisation of pause points the use of a clustering algorithm was investigated, to determine whether or not this proved to be a useful statistical method. The method that was used was the k-means clustering algorithm and it was determined that it could be used effectively to identify groups or clusters of pause points. It was felt that although the use of this method did appear to achieve its goal, that is to identify any clusters of points, it was not felt that it performed any better than a researchers intuition. It rarely revealed patterns that would not have been evident simply by examining a visualisation of the points. Moreover, it was felt that since the algorithm did not take into account the spatial layout of the environment it could sometimes attribute a number of points to a cluster, when clearly they bore no relation to one another because they were spatially separated (perhaps by a visual barrier such as a wall). For this reason, it was concluded that although it had been a useful tool to investigate it really contributed little to the thesis as a whole. However, for future applications, where much larger data sets may need to be analysed over a larger number of worlds, then such an automatic method of cluster analysis could prove useful. Ultimately were it possible to combine some sort of cluster analysis alongside a form of spatial analysis, then this could prove to be an even more useful method of analysis. For example, it could be proposed that the first test of whether or not a point should be assigned to a cluster is if it is visible to all other points in the cluster. This would not only combine a variant of cluster analysis but also include the types of intervisibility relationship discussed in the previous chapter, Chapter 8.

A quite significant result of the chapter on pause points was the fact that a comparison of total journey time or distance travelled to stopping patterns may reveal individual characteristics of journeys. This was never developed further since it was not felt to be central to this thesis. However, it appeared, that it could be possible to discern characteristics of a number of journeys, indicating possible strategies of different subgroups of people. In the experiment presented in the thesis it was suggested that the results could be showing both gender, age and left/right-hand biased differences in navigational patterns. Without question, this could certainly be an avenue for future research, since gender differences in navigation strategies and abilities are often discussed and do form the subject of certain psychological investigations.

Almost through an accident, another possible research finding from this thesis became evident. Based on data from two of the seven worlds in this thesis, it could be suggested that there is a possible correlation between the speed of a subject's movement and the duration of their pause points. The faster a person moves, the less time they are likely to spend stationary. This finding came about, when towards the end of a series of experiments, subjects were shown how to move faster (the full explanation for why the experiment was conducted in this manner can be found on page 66). The result of this increase in pace appeared to produce a hitherto unanticipated decrease in the duration of pause points. It was not that people were pausing any less frequently, it seemed rather that people were merely pausing for shorter amounts of time. It was as if their judgement of time was modified through their speed of movement. This could without doubt be a factor worth future investigation, particularly when researching navigational patterns in virtual worlds as a stand-alone research area. This could be regarded as a distinct area of research in opposition to this thesis, whose focus is to investigate virtual world navigation in the context of the light that it may shed upon pedestrian movement in the real world. There may be future applications for the results of research such as this by designers of virtual worlds. Even today, there are designers who are being commissioned to design virtual worlds that need to function appropriately, virtual worlds that *are* the design product (rather than an interim stage to an ultimate realisation in the real world). For example the work being done on collaborative virtual environment at the University of Nottingham or at the BT Research Laboratory. These are worlds that are inhabited and support a range of activities and social interactions. If it is verified that a subject may pause less frequently or for reduced periods of time, depending upon their pace, then this could have a direct effect upon the design of these virtual worlds.

Another set of conclusions that arise from the detailed examination of pause point locations concern the differences between urban areas and buildings. It was surmised in Chapter 7, that there may be possible differences between stopping behaviours in a building and at the urban environment level. These differences may be investigated through analysis of the duration of pause points. It appears that people are pausing more frequently in a building than in an urban system. One possible conclusion that can be drawn from this is that a time interval that constitutes a significant pause at the building level may not constitute a significant pause at the urban level. It may either be the scale of the environment that is producing a difference in stopping patterns or it may be that there is a more rapid rate of optic flow (to use Gibson's terminology) in a building, the visual stimuli are changing more rapidly and therefore there is a need to pause more often to reassess these changes. Once again, this could provide a useful research question prompting new research directions. The use of virtual simulations of urban districts and buildings to determine differences at the micro-scale level between the different environments.

It is also possible that people pause in different types of locations in buildings and urban systems. In an urban environment, people appear to be pausing in proximity to road junctions. Any analogous behaviour is hard to discern at the level at the building. However, if the results of the Tate Gallery are compared to the locations of pause points in urban environments then it can be seen that people are pausing towards the centres of spaces (areas of below average isovist drift). These locations could be regarded as optimal locations for making route choice decisions in a building, since in the centre of a room, it is possible to look around as see through all doorways into adjacent rooms. It is less likely that a route choice decision is made at a door threshold in a building, whereas due to the difference in scale, it is entirely plausible that such a decision be made at a junction in an urban environment. For this reason, it may be that the finding that people pause in the centres of spaces in buildings is a manifestation of the same effect of subjects pausing at junctions in urban environments.

After determining that people appeared to be pausing in, or in close proximity to road junctions, it seemed that it could be a useful exercise to determine whether or not road junctions could be characterised through attributes of isovists generated at these locations. The conclusion of this analysis was that junctions appeared to be able to be characterised as areas of high mean isovist radial length. For certain environments, other measures may also be good indicators of junction locations; mean radial length, however, appeared to be a consistently good indicator over the sample of seven worlds. It is not that junctions are characterised by the areas of highest mean radial length, but rather there is a consistent identifiable increase in this measure at junctions, when compared to adjacent streets.

The observation that people appeared to be stopping at junctions and that these may be areas of high isovist mean radial length, led to an attempt to develop a typology of junction type based on its isovist's properties. This was proposed firstly as a useful method for examining people's behaviour; people's decisions at junctions can be examined in the context of the junction type (see Appendix B for a description of these proposed typologies). It can also be regarded as a fulfilment of Benedikt's prediction that isovists could be used in this way, namely to characterise different types of spatial arrangement.

Upon suggesting that it should be possible to develop an enriched typology of road junctions, it was then suggested that it should be possible to take a real world junction-isovist and fit it to one of the idealised junction-types (also see Appendix B). One possible application for this technique could be the automated mapping of road configurations. It should be possible to generate a series of isovists (either randomly or on a grid) such that all navigable space contains at least one isovist viewpoint (and ideally a number of points). The isovist resolution, as expressed by the number of isovists per square metre, or the grid divisions, can be varied. Once the areas of suspected junctions are identified (for example through the attribute high mean radial length), the individual isovists can then be matched to the idealised junction types. Once a match is confirmed, the junction location can be stored as well as the number of roads forming it and their angular distribution. The technique that proved most useful for achieving this goal was the use of the mathematical technique known as canonicalisation.
Canonicalisation essentially describes the technique of matching any real-world junction to a canonical (or idealised) example. An example of how this technique might be applied to junction types was successfully illustrated by a real world example. By using such an automated environment mapping technique, an environment could be represented as a simple graph representation. Each junction could be represented as a node in a graph and every street (or uninterrupted line of sight) represented as a link in the graph. This suggested application of the technique of junction identification to environment mapping, is very similar to the method used by Kuipers, in his paper (Kuipers and Byun 1991) except that Kuipers used SONAR instead of visual fields, and his mapping robots were mapping real environments. The potential for an automated environment-mapping tool is high, and for this reason, this should be regarded as a potential area of research stemming from this thesis.

To complete the body of work conducted with junctions in urban environments, it was queried (in Appendix B) whether or not the shape of an isovist as generated at a road junction could be described by a mathematical equation. The conclusion was that junction shapes could be described by equations by using a polar graph and generating variations of the absolute value of the reciprocal of the cosine of theta. Ultimately it could be possible not only to automatically identify the locations of junctions in an environment, but also to record their exact shape as a mathematical equation. In this respect, an urban environment could effectively be described in an extremely succinct and economical manner. It could be possible to store descriptions of many urban environments extremely efficiently. However, to achieve this goal further research into fitting mathematical equations to junctions would need to be undertaken.

As a method for further linking single isovist properties to Space Syntax research, it was demonstrated statistically that certain attributes of the geometric shape of isovists correlated extremely well to syntactic measures of isovists. The implication of this is quite significant. It implies that it should be possible to infer properties of the configuration of a whole system from the visual field of the single isovist in which an observer is standing. This direct connection between the global and the local properties of isovists may confirm long held ‘hunches’ by Space Syntax researchers. However, a confirmation of the ability to make inferences about the interrelationship of spaces from nothing more than the single isovist that is immediately perceivable, is a finding that is quite remarkable. The very fact that there is also a correlation between pause points locations and specific isovist data only serves to reinforce that this is indeed a significant finding.

The connection between isovists and pause points was determined towards the end of Chapter 8 (the previous chapter). At an earlier stage in this thesis, it had been observed that people appeared to be pausing in or in close proximity to road junctions. However, this observation was purely subjective, prompted by the method of visualising pause points as dots on a plan. In this chapter, however, this observation was tested statistically. Both the central limit theorem and the z-test were applied to the task of determining how representative of the population of grid isovists (flooding all navigable space with isovist viewpoints) was the sample of isovists generated at pause point locations. The conclusion of this exercise was that people appear not to be pausing randomly in terms of isovist properties. It could be seen that on the whole, subjects were pausing in locations that offered strategic visual properties. These were locations that afforded unusually long lines of sight and large isovist areas. They were isovist locations that were highly integrated within the system, as well as highly connected and finally it appeared that people were pausing in locations that were far from any occluding surfaces such as building edges. The overall conclusion was that people were being exceedingly strategic in terms of where they stopped to scrutinise the environment. They paused only in locations that offered the maximum visual, local and global information about an environment, reducing the necessity to pause more frequently. The manner in which people navigated through an unfamiliar environment could therefore not only be seen as being strategic but also maximally efficient. It was demonstrated how such actions could cumulate into aggregate patterns of movement consistent with patterns of spatial integration.

This thesis has focussed on the question of whether it is possible to learn from behaviours in virtual environments how people are likely to behave in the real world. This chapter, in turn, will make some suggestions, not only for how this research might be applied, but also put forward some ideas for future research directions.

Future research directions and applications

Firstly, it is essential that the work of this thesis be continued as only seven worlds were used in the experiments, which is a relatively small number, and only two of these worlds were simulations of real environments. Although this thesis provided an excellent starting point for such research by suggesting that real and virtual patterns of navigation were analogous, this body of data represents only initial research steps. It is highly likely that the relationship between the two patterns is not a direct one. It may be that people's behaviour in a virtual world does differ somewhat from real world pedestrian movement. The precise nature of this relationship should continue to be explored. It would be unfortunate if the conclusions of this thesis were to be taken at face value and further work were to be undertaken simply assuming that one implied the other.

One way in which to undertake continued research into the relationship between real and pedestrian movement could be quite simply achieved. Every time a real world building or urban environment were analysed and pedestrian movement recorded (either as pure research or as consultancy) then an equivalent, virtual environment experiment of the same building or urban area could be conducted. If virtual world experiments shadowed real world observations, then over time a database of equivalent movement traces could be established. This would assist greatly the understanding of the relationship between pedestrian movement in the real world and patterns of virtual navigation.

There is another method that could be used to gather virtual movement data. Ruddle conducted experiments demonstrating no discernible difference between how people navigate in desktop virtual environments and immersive worlds (Ruddle, Randall et al. 1996). A future scenario can be imagined where a model of a proposed building is put online, for example in VRML format. The intended, future users would then be able to log on and navigate through the world, and the paths of their movement could be emailed back to the architect or researcher. In this way, the building model serves a dual purpose. Firstly, it acts as a method of liasing with and informing the would-be end users, a kind of public consultation exercise that is particularly approved of at the moment by Planning Authorities. Secondly, it becomes a means for the architect to generate data about how the real building might be used prior to its completion hence allowing time for design modifications before being constructed.

As it is essential to continue to determine whether or not there are similarities between real and virtual world navigation, then it is necessary to improve upon the current methods of real-world movement observations. At the moment, the kinds of data available from virtual experiments are far more detailed and precise when compared to real world observations that are mostly made by hand. For the kind of work undertaken in this thesis to continue, the quality of the real world observations must improve so that the two data sets are equivalent. The types of methods that can be used and developed for this purpose are techniques such as the use of active badges, video capture/analysis, infrared beams and pressure pads. This is a prime area for future research.

In all of the worlds that were used in this thesis' experiments, the subjects were walking around alone. The potential for using virtual reality techniques to investigate the effect of co-presence upon behaviour, particularly navigation, is a potentially exciting future direction. There are a number of ways of investigating this. Firstly, it could be possible to set up a series of observations inside online, collaborative worlds on the Internet (for example, AlphaWorld). They could be used to investigate the role of the environment and spatial design of the worlds upon navigation, chance encounter and casual meetings. This could serve to progress work already being conducted into this area by Huxor (Huxor 1998). Another direction that could be taken is to 'stage' a number of experiments. For example, if the following hypothesis were to be tested, namely that 'people simply follow people'. The testing of this could be achieved through the use of a world where certain streets were highly populated (with avatars) and other streets quite empty (whilst keeping all other variables constant) and then to determine if people choose to take the seemingly more 'popular' route over the choice of the less 'popular' route. This would effectively be testing the idea that people create a 'multiplier effect'; that we are more inclined to take a route if people are already present. It would also be interesting to determine whether there might exist gender differences in the results of such an experiment and it could be a useful way in which to investigate individual perceptions of personal safety.

It is hoped that in the next few years more sophisticated eye tracking equipment might be easily available. If it were possible to combine eye tracking equipment with a head mounted display then it would be possible to gauge precisely where subjects look as they are moving around instead of their approximate direction of gaze. This option was investigated at the beginning of the experimental work undertaken as part of this thesis, but it proved impossible to achieve. Technologically it is currently *just about* possible to make these kinds of measurements in both the real world and the virtual world. Such additional information could be particularly informative. For example, it could be possible to identify locations where people make route choice decisions and to determine what environmental features they look at in order to inform their decision-making. This information could not only be useful for urban designers but would have an immediate application for producing effective signage in large, complex buildings such as airports.

All of the above suggestions for future research were concerned with alternative methods of gathering real and virtual observation data. There are also a number of possible areas of research that arise from the methods of analysing such data. All of these future directions were prompted by work done in this thesis.

If much larger data sets were to be analysed, then it could prove useful to further develop the methods of cluster analysis used in this thesis. Ultimately, it could be possible to combine a variation of cluster analysis with methods of spatial analysis. For example, as it was suggested earlier in this chapter, it could be possible to test whether a pause point should be assigned to a cluster depending on whether it were visible to all other points already belonging to that the cluster. This would effectively combine a variant of cluster analysis with a measure of intervisibility/isovist relationships.

It has already been mentioned in this chapter that it could be possible to use virtual reality technology to investigate gender and age differences of navigational strategy. Another interesting area for research would be to determine whether or not there are differences between subjects with varying experiences of virtual environments. For example, to investigate differences between people who are particularly used to navigating through virtual worlds, such as computer-game players, and those for whom the technology is quite unfamiliar. This research particularly prompts the question of whether future generations who are growing up, utterly familiar with such technology, would ultimately demonstrate different behavioural characteristics of virtual navigation. Could these differences effect real world behaviours too?

One set of experiments that could arise from this thesis would be to investigate the effect of speed upon stopping behaviour. It would be extremely useful for designers of virtual environments to be able to determine if people pause for briefer periods of time if they are moving at a faster rate. This would be relatively straightforward to test. It could also be interesting to use virtual simulations of urban districts and buildings to determine their different effects upon micro-scale behaviours. Do we use urban space in the same manner that we use buildings, or does there exist identifiable differences?

Another pair of connected research areas is concerned with the generation of efficient representations of environments. Firstly, the potential for an automated environment-mapping tool is high, and for this reason, this should be regarded as a valid area of research stemming from this thesis. An automated environment-mapping tool could be based upon isovist analysis of environments, and then using this data as a basis, to identify and record the location of road junctions. Lines of sight and/or streets connecting junctions could be represented in graph-form or by the use of mathematical equations to describe junction-shape. The second area of work involves the further development of mathematical equations to describe road junctions.

A particularly interesting area of future research would be to investigate the phenomenon termed route angularity by using virtual worlds. In particular it could be possible to determine whether or not 'seven plus or minus two' junctions or changes of direction were significant. The use of virtual environments lends itself particularly well to this task, as it would be possible to generate a number of theoretical routes, all of precisely the same length, yet expressing a range of changes of direction. Once again, this would be a particularly straightforward set of experiments to create.

The analysis performed in Chapter 5, using string matching, could be further developed. In Chapter 5, the strings were used to represent the spaces through which subjects passed. It was also suggested in Appendix A that this technique could be applied to local decisions made by people, for example to represent the act of turning left or right. This could be used as a method for analysing the kinds of decisions being made. If string matching analysis (Chapter 5) were combined directly with route choice analysis (as in Chapter 6) and perhaps also combined with canonicalisation of angles (Appendix B) then the local strategy of people could be analysed as well as their global strategy. In this manner, someone who consistently took a left turn followed by a right turn could be regarded as being identical (in terms of local strategy) to a second person making the same turns but in a completely different part of an environment.

It could be interesting to perform the same kinds of experiments as performed in this thesis but to record other human-response data at the same time. Data that could be simultaneously recorded, and could broaden our understanding of how we navigate through environments, could be body temperature, heart rate, a subject's verbal discussions of their experience and the activity of certain parts of the brain. This is an approach that is already being taken by O'Keefe et al. on hippocampal activity during navigation (O'Keefe and Burgess 1996). There is, however, scope for more work to be done in this area.

Since this thesis investigated the micro-scale behaviours that result in the aggregate patterns of pedestrian movement that have been observed in buildings and cities, it could be possible to translate these micro-scale behaviours into a set of rules. These rules could be used as the basis to programme cellular automata or virtual 'people' (agents) who would be able navigate environments in a manner similar to real people. There are a couple of applications for this approach. Firstly, it could be a useful method to further pedestrian movement research. If the micro-scale behaviours recorded in this thesis could be translated into a set of rules and then the resultant patterns of movement were found to correlate with real pedestrian movement then this would validate the rule-set. The second application for which this could be used would be to populate virtual environments with virtual people who would be able to navigate in a natural manner. A criticism that is often levelled at architectural drawings and photographs is that they are often devoid of people. If these micro-behaviours were to be successfully translated into rules governing avatar behaviour, then architects could present a client images, movies and real-time walkthroughs of a design that was fully populated with virtual people. This could give the client a far better idea of how the final building would appear.

One of the more interesting measures to have emerged from the isovist analysis was 'drift'. Drift is the distance in length of a line connecting the viewpoint of an isovist to its centre of gravity. The patterns formed by areas of minimum drift tended towards the centres of spaces and roads were incredibly suggestive of patterns of pedestrian movement, sufficient paths and axial lines. It would be particularly interesting to investigate whether drift could be connected to sufficient paths and axial analysis.

Finally, the methods introduced in this chapter for analysing environments using isovist arrays, and correlating this data with micro-scale behaviours of people could, without question, be continued and developed. When Benedikt discussed the potential for conducting research of this kind in his paper (Benedikt 1979), it was particularly difficult to record adequate data of people's behavioural patterns in such a manner that they could be correlated to isovist properties. The use of virtual environments to achieve this goal has been suitably demonstrated in this thesis and it is to be hoped that this work may be continued.

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Appendix A: Further Applications of String-matching Techniques

Chapter 5 concentrated on a methodology for the calculation of a unique measure for each route in set of routes through an environment, such that it is possible to isolate any single route and determine how similar it is to every other route in the sample, or indeed how distinct from every other route. In addition to the calculation of an MNLD value for each route, it is also possible to determine a single measure for the sample as a whole. This is the mean of all the 'MNLD' values for all the routes in the sample. The reason for calculating a sample-wide MNLD value is that this enables the comparison of two distinct samples of subjects. It is then possible to determine whether one group of people behaved in a more homogenous manner when compared to a second group of people. The sample-wide MNLD value can therefore be held to be a group homogeneity measure.

Perhaps more usefully, a natural derivation of the sample-wide MNLD value is to take a sub-sampleof a group and determine how representative of the main sample, that sub group is. To illustrate this application, imagine an experiment involving a series of observations of a group of people moving around a sample area. Three types of people are observed separately (men, women and children). It would then be possible to calculate a sample-wide MNLD value for all the persons observed. Let this be denoted by X. A sub-sample MNLD value could then be calculated for the two sub sets, women and children. Let these values be Y and Z respectively. If Y or Z were to be less than X, it could then be stated that the subset of women or children behaved in an *identifiably* more homogenous manner than the group as a whole. This method of analysing sub groups, could be key to the identification of certain behavioural characteristics of such groups.

Another second possible application of this string-matching method is to compare *both* local and global similarities between routes. In the experiment presented in Chapter 5, the criteria for converting a route into a string, was based on global information about that environment. It would, however, be possible to undertake the exact same process of converting a route into a character string using local, not global measures. One example of how this conversion might be achieved would be through the use of a set of four (or more) ASCII characters depicting local decisions. The following small example uses 'L' to represent a left turn, 'R' = right turn, 'S' = straight on (Past a turn that could have taken but was ignored) and finally 'T' = 180° turn on the spot. In this manner, it would be possible to exactly represent any route taken by an individual, such that any journey could be reproducible.

If all routes were to be transcribed using local information, then the routes that might be defined as similar to one another, might not be similar in terms of the *absolute* routes taken, but instead could indicate a similarity in the *strategy* of the subjects. Take for example the two following characters strings representing routes taken, L-R-L-R-L-R and R-L-R-L-R-L. In both these cases, the subjects have attempted to find their way through an environment by alternating left and right turn decision choices. Were these journeys to be plotted as route traces on a map they might pass through entirely distinct spaces, and hence would be considered to be completely dissimilar using global string-matching, as indeed they should. However, if the local strings were to be compared then the Levenshtein distance between these two strings is only two. In other words at the level of the local decision, these two subjects are behaving in a very similar manner. This could be a useful technique for identifying local strategies and also for moving between local and global measures yet retaining the same tools of analysis.

Appendix B:
Typology of Junction Types Based on Isovist Shape

Abstract

This appendix explores the characteristics of isovists generated at road junctions. Its starting point is an 'unfurled' isovist namely, a line graph composed of sequential isovist radial lengths. The appendix goes on to propose a method for identifying the number of maxima in the graph and hence extracting the number of roads radiating from the junction. Once real world data is used a method for 'smoothing' the graph is required and a technique that uses 'running maxima' is presented. Once the number of roads has been identified, the radial distance between them must be established and this information is used to match the junction to an idealised type using a method called canonicalisation. This appendix concludes by presenting a method for generating mathematical equations to describe junction types.

Introduction

Chapter 7 considered patterns of stopping behaviours of people. One conclusion of this chapter suggested that people were pausing in, or in close proximity to, road junctions. From this observation, one question emerges, which is that, if people are stopping at junctions, can these junctions be characterised by any specific visual qualities? Is there a method of describing junctions through their isovist properties? This detailed examination of isovists at junctions leads to the development of an expanded typology of road junctions based upon their isovist attributes. This analysis of junction isovists is covered in this appendix.

The vocabulary that is currently available to architects, urban designers and traffic engineers for describing road junction types is extremely limited. There exist only three broad categories of named-junction type, these being the 'crossroad', the 'T-junction' and the 'fork'. When utilised for the purposes of issuing verbal instructions to strangers navigating through a city, these three terms are probably sufficient if modified by an occasional, judicious, descriptive detail. "…The fork with the King's Head pub to your left…" In Chapter 7, however, it was suggested that people appeared to be pausing at or in close proximity to road junctions. For this reason, if it were possible to be able to categorise junction types more accurately, then this could assist greatly in describing or seeking patterns in such stopping behaviour. Therefore, the development of an enriched typology of road junction could be seen to be a useful tool for investigating such stopping behaviour. In (Benedikt 1979) he describes conceptually the possibility of being able to uses isovists in a number of ways.

> "…To predict trends, optima, and limits on a variety of possible spatial behaviours and perceptions in a given environment, …to assess some basic spatial qualities of environments whose conscious or unconscious apprehension may guide or underlie 'higher' cognitions and behaviours,"

The intention of this appendix, namely to see how far people's stopping behaviours (in terms of isovist properties of the environment) can be held to be a direct response to Benedikt's description. Towards the end of this paper, he concludes by describing how it could be possible to categorise a number of named building space-types through their isovist properties.

> "…One should note that 'kinds of space', such as 'hall', 'corridor', 'colonnade', 'court', 'plaza', and so on, might in good part be *definable* in terms of the kinds of isovists and isovist fields they generate."

To this list of both interior and exterior spaces could be appended the space type 'road junction'. One interpretation for the act of developing such a typology of junctions (as proposed in this appendix) is as a means of fulfilling Benedikt's prediction of an expanded space 'taxonomy' through the act of 'filling-out' a specific sub-classification. In this particular case, the proposal is to expand the sub-category 'junction' into a whole family of types. See figure B.1 below for suggested 3-road and 4-road junction types. (Obviously there are also five, six and n-road junctions but since these are rarer this appendix will focus upon these two types.) Suggested nomenclature is included on the diagram.

Equilateral Fork Obtuse Fork Acute Fork

T-Junction Asymmetrical Fork Asymmetrical Fork 2

Crossroads Asymmetrical X-Junction X-Junction

Acute K-Junction K-Junction Obtuse K-Junction

$r = f(\theta)$ where $r^2 \equiv x^2 + y^2$

Right-angled Psi-Junction Asymmetrical Psi-Junction Psi-Junction

Figure B1 Types of Junction

The array of junction types illustrated above is based upon either three or four road junctions, namely junctions formed by the convergence of either three or four roads. The first two rows are three-road junctions and the last three rows are four-road junctions. This is not a definitive list of *all* possible three and four road junctions, since there will be a natural variation of the angles between roads. This is, however, a representative set that is based upon 180°, 90°, 60°, 45° and 30° angles between road centre lines. Other real-world junctions can be held to approximate one of these primary types.

Having determined these basic types, it is then possible to generate an isovist taken at the very centre of each junction. By generating the characteristic isovist for every junction type, it should be possible to specify a method for determining the junction type based solely on the isovist's shape and attributes. If it is possible to identify the junction type based upon isovist characteristics alone, is should be possible to automate this task. If this method were to be taken to its logical conclusion, it could ultimately be possible to analyse an urban area, by generating all possible isovists in navigable space, and then matching each isovist against these idealised types. In this manner, junctions and their connections could be identified and a graph representation of the environment formed. This could prove a useful basis for environment analysis that is not dissimilar to methods already being used by Kuipers in his paper (Kuipers and Byun 1991) except that Kuipers uses robots navigating through the real world and sonar[1] to develop his 'isovist' representations. In Figure B.2 Overleaf are shown the isovist data for the fifteen junction isovists. Each junction isovist is represented by two types of graph. The first graph, and the most easily recognisable as an isovist, is a polar plot of the lengths of isovist radials. Each isovist is generated from the centre of junctions. Visually this looks exactly like the isovist – or junction on plan. Once the polar plot has been created, the isovist can be 'unfurled'. Instead of the radial lengths being plotted as a polar plot, they can be plotted as a simple line plot, with the degrees

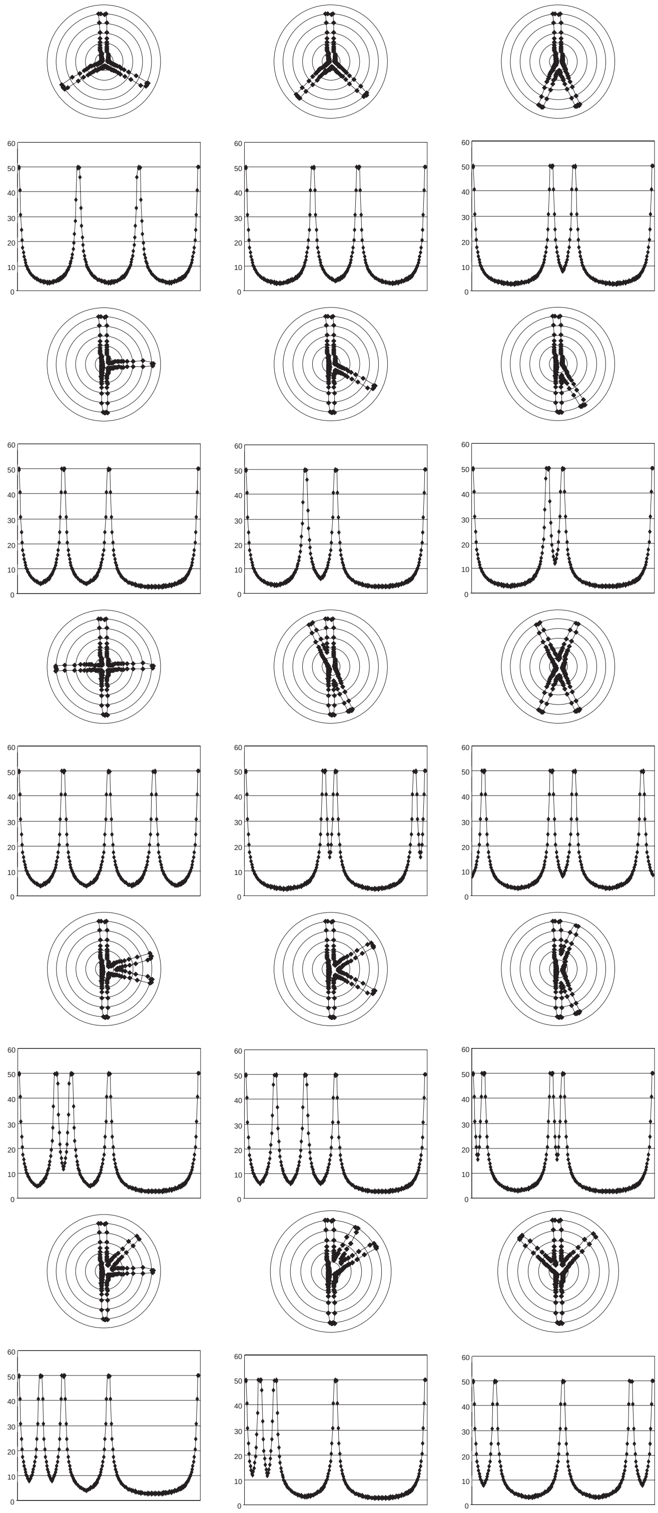

Figure B.2 Graphs of Radial Lengths for Junction Isovists

between radials marked along the x-axis and the length of the isovist radials in metres (or lines of sight) plotted along the y-axis. Once the line plot representation has been generated, this can then be used as a method for characterising all junction types from their isovist line plots. Figure B.2 above show the polar plots and unfurled-isovist line plots for the fifteen junction types presented in figure

B.1. From figure B.2 we can observe certain graph characteristics of these plots. They all take the format of an irregular wave format. There are a number of maxima and a number of minina. The y-axis value of the maxima represents the longest possible line of site; the value of the minima represents the distance from the observer to the nearest built edge. In the case of the fifteen junction types illustrated previously, the maxima and minima are all of the same value, however if this were not the case, the greatest maxima would represent the longest line of sight and the shallowest minima would indicate the least distance from a built edge. The number and distribution of the maxima along the x-axis are the keys to the junction type. The number of maxima are the number of roads converging, so that if the number of maxima is four, then the junction will be a cross roads of some type.

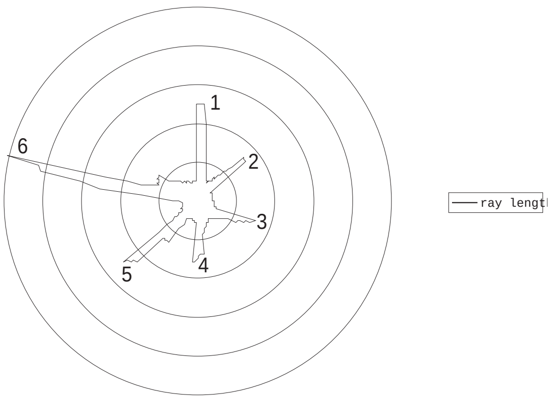

Figure B.3 Polar Graph of Isovist Radial Lengths

If we are using real-world data instead of using the idealised versions then the first stage is to identify how many minima and maxima there are. This can be more difficult than it seems. Consider the example overleaf. This is a typical real-world junction, in this case taken at the point where six roads meet (although the canonical examples all comprise of four roads or less, a six-road example is now used as a maximally complex test of the following method). The fact that this is a six-road junction is quite clear from the plan of the isovist. See figure B.3 opposite.

However, the next stage is to try to formulate a reproducible method of characterising this as a six-road junction. If we unfurl the isovist and plot it as a line graph, figure B.4 illustrates what it looks like.

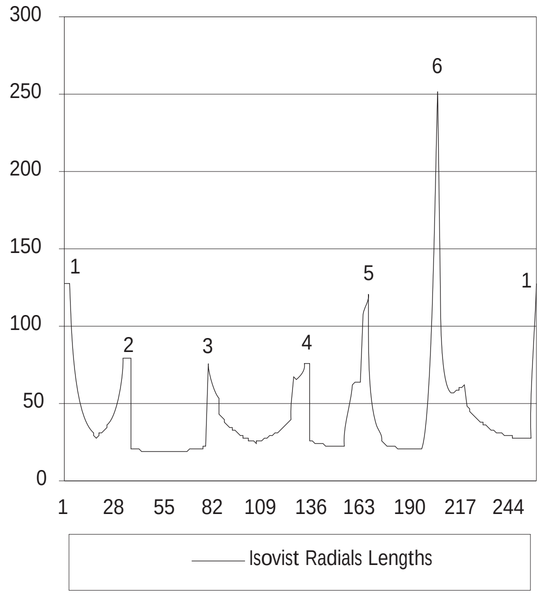

Figure B.4 Line Plot of Radial Lengths

The maxima (at different heights, representing different length lines of sight) are marked onto the graph, numbered 1 – 6. Unfortunately, there is a lot of noise in this data, formed by a variety of occluding surfaces. These appear as small, localised maxima or minima on the graph. If a simple maxima-finding algorithm were to be used (such as a hill-climbing algorithm), it would also highlight these smaller maxima, leading to a conclusion that this junction was possibly a ten-road junction rather than a six-road junction. It is possible to 'smooth' the data using a technique that calculates a moving average. The technique takes a number of points either side of each point (for example five points either side) and calculates the average value of all the adjacent points. This new value is then used to generate a new column of data, which is the data used to produce a new line plot. This process is repeated for all points in the sample. Although this does smooth a sample very well, it still does not completely eradicate all localised maxima and minima, and can reduce the height or even erase some true maxima altogether.

If an alternative technique is used, that calculates running maxima', this produces a more successful result. As before, a new set of data is derived from the first set. For each point, five[2] points either side are taken and the maximum value of these eleven points is calculated. The equivalent point in the derived data is set to this maximum value. This process is continued for all the data, remembering that the data wraps at either end (since the isovist is continuous). If we apply this technique to the isovist above, and plot both the original data and the running maximum set of points on a single graph, then the results can be seen on figure B.5 below.

This method has actually removed any local maxima and minima. Any standard maxima finding algorithm would now find the six maxima. In this case, it would find six, and only six maxima, concluding that this were a six-road junction.

The second stage is to determine the radial distribution of the maxima. Still using the isovist example from above, having found each maxima, it would be necessary to note the value in metres (y-axis) of the maximum radial. In the derived data set there would be a number of points sharing the same maximum value, at least eleven points in this example. It would then be necessary to return to the original data to determine which were the data points of maximum values within each identified maxima. Another method to identify these maxima would be to perform a moving average calculation after the running maximum calculations. The combinations of these two methods in sequence will not only remove any localised minina, but will also identify the locations of the maxima. Note that these techniques will only function is they are performed in this order, and not if the order is reversed. The

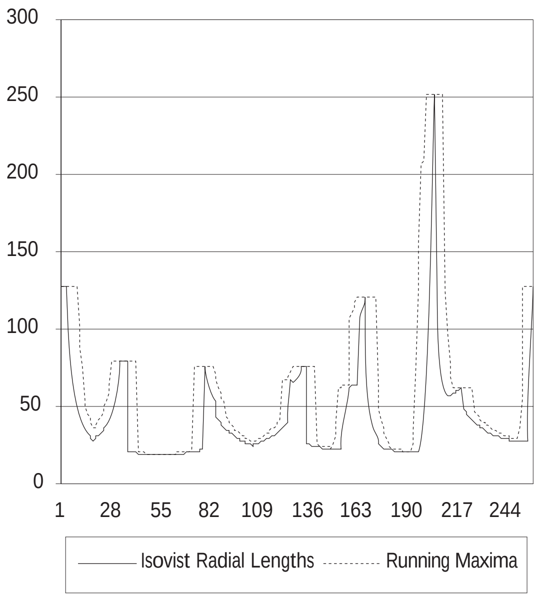

Figure B.5 Running Maximum of Line Plots

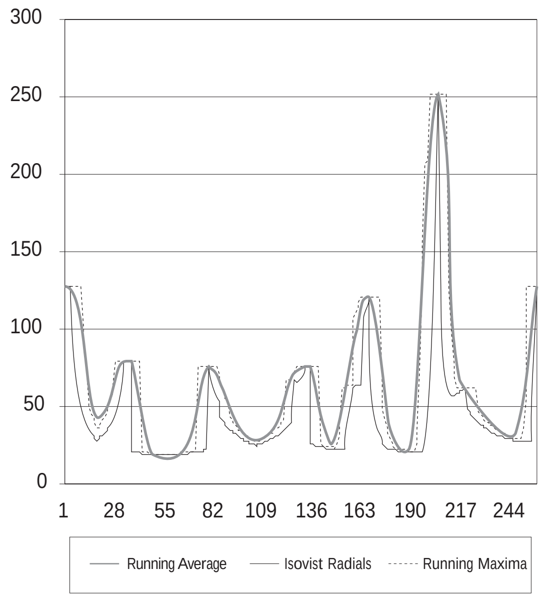

Figure B.6 Running Average of Line Plots graph shown in figure B.6 overleaf illustrates the moving average line plot superimposed over the original data and the running maximum data.

Once the positions of the maxima have been identified (using either method) then the distance between them (in degrees) can be calculated from the graph. For example in the previous example, there are six maxima, distributed radially with the following degrees between them. [38° 67° 71° 46° 67° 71°]. This data can be shown superimposed on top of the line graph, as the widths d1 – d6.

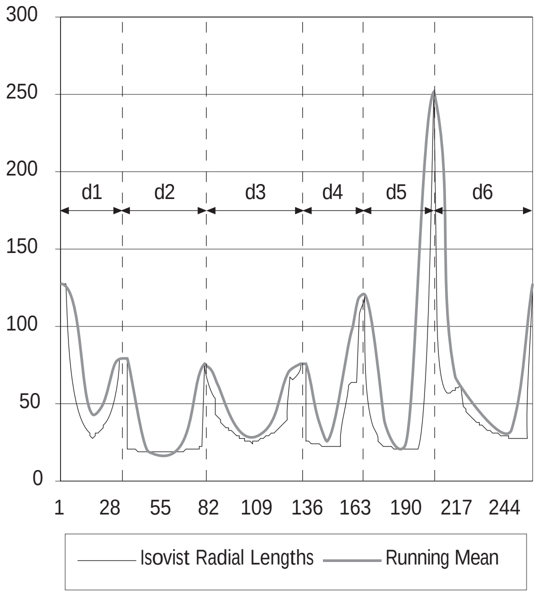

Figure B.7 Widths Between Road Centres

So if it is possible to generate an isovist at any real-world junction and then identify the number of isovist maxima or roads forming the junction, let this be called n, and the radial distribution of the roads, how do we match this data with the ideal types introduced at the beginning of the appendix? We use a common mathematical method termed canonicalisation or the classification of objects by identifying canonical examples and devising a technique for equating each object to one of the canonical examples. For example, the canonical examples could be the fifteen junction types at the beginning of this appendix. The next section of this appendix will illustrate how to match any real world to the canonical examples.

The first stage is to express each junction in terms of the angles. Each junction can be expressed very simply in terms of the angular distance between the maxima, as identified from the junction's isovist. For example a standard crossroad would be described at [90° 90° 90° 90°]. The next stage is to round the angular difference to the nearest degree. For example, it is obvious that the two junctions [90° 90° 180°] and [90° 91° 179°] are both T-Junctions, with almost no difference between them. In the idealised examples at the beginning of this appendix, the angles between road centre lines are all multiples of either 30° or 22.5° degrees. The second stage, therefore, is to round each real-world angle to the nearest 30° or 22.5°, and then express the junction in terms of their rounded angular differences. If we take the real-world example above, the distribution of the maxima could be expressed as [38° 67° 71° 46° 67° 71°]. After being rounded to the nearest 30° or 22.5° degrees it becomes [45° 67.5° 67.5° 45° 67.5° 67.5°]. Note the two points regarding this rounding exercise. The sum total of the angles still equals 360° and that 67.5° is calculated by multiplying 22.5° by a factor of three. The graph below shows

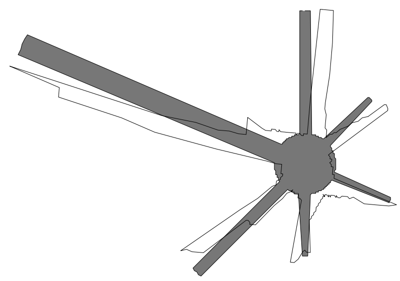

Figure B.8 Original Isovist Matched to Canonical Isovist the real world isovist superimposed over its canonical-angled equivalent isovist coloured grey (figure B.8).

The final stage is to rearrange the angles so that the ordering begins with the smallest angle first. So, for example in the case of these three junctions [45° 135° 180°], [135° 180° 45°], [180° 45° 135°] by rotating them so the smallest angle is first they all take on the same format, [45° 135° 180°]. If there is more than one smallest angle, pick the smallest next angle so [45° 90° 45° 180°] is preferred to [45° 180° 45° 90°]. In this manner, it does not matter which road is considered the first maxima, nor does it matter whether the isovist is swept in a clockwise or in an anticlockwise manner, two similar junctions will be judged equivalent.

Here are the original fifteen junction types but this time expressed in canonical form.

[45° 45° 135° 135°]	Psi-Junction
[30° 30° 120° 180°]	Asymmetrical Psi-Junction
[45° 45° 90° 180°]	Right-angled Psi-Junction
[22.5° 135° 22.5° 180°]	Obtuse K-Junction
[60° 60° 60° 180°]	K-Junction
[30° 75° 180° 75°]	Acute K-Junction
[45° 135° 45° 135°]	X-Junction
[22.5° 157.5° 22.5°157.5°]	X-Junction 2
[90° 90° 90° 90°]	Crossroads
[30° 150° 180°]	30-degree T-Junction
[60° 120° 180°]	60-degree T-Junction
[90° 90° 180°]	T-Junction
[45° 157.5° 157.5°]	Acute Fork
[90° 135° 135°]	Obtuse Fork
[120° 120° 120°]	Equilateral Fork

Strictly speaking, the final angle is unnecessary since all angles add up to 360°, and hence the final angle can be inferred from the other (n-1) angles. However, it helps the process of sorting the angular distribution of all roads constituting any junction. Once the canonical examples have been described in terms of their angles then any real-world isovist can be expressed in a similar manner, and matched against these examples. For example, it could be possible to automatically deduce that a certain junction is a type of fork as opposed to a T-Junction. By measuring the heights of the maxima, it should be possible to distinguish the isovists at the very centres of junctions compared to isovists near the end of streets, which can begin to exhibit junction-like characteristics.

Equations for junctions

As an addendum to the previous section it might be suggested that there could exist a way to describe some of these isovists through equations. Those that are most easily described could be regarded as the 'platonic solids' of junction-types.

The two equations presented in this appendix as being suitable junction-generating equations use polar graphs rather than Cartesian co-ordinates. For this reason, the equations take the form

$$r = f(\theta)$$
$$where$$
$$r^2 \equiv x^2 + y^2$$

Equation B.1

Theta is the positive angle described between the x-axis and a line connecting the point to the graph's origin, were r indicates the length of the line or the positive square root of the sum of x-squared and y-squared (Pythagoras). Presented below are two equations used to generate platonic-junction types. Their relationship will be demonstrated overleaf. The first equation takes the form,

$$r \geq \left| \frac{1}{(cos - 0.5\theta n)} \right|$$

Equation B.2

Where n is the number of roads forming the junction, i.e. when n=4, the junction is a crossroad. This particular equation describes a region, hence the inequality. In figures B.9 oppposite, the radiating lines are generated using the above equation. The other graph superimposed upon the first is plotted using the second equation, below, which more closely resembles the polar plots of the fifteen suggested idealised junction types.

$$r = L_{max} tanh\left(L_{min} \left| \frac{1}{(cos - 0.5\theta n)} \right| \right)$$

Equation B.3

The second equation is a modified version of the first equation but includes two additional variables, L_{max} and L_{min}. These numbers represent the maximum radial length and minimum radial lengths. In the graphs overleaf, they refer to the values of the curve's maxima and minima. The variable n refers to the number of roads constituting the junction. When n is an integer, and is inserted into the equation, it generates the 'platonic[3] junction types'.

N = 0	enclosed space
N = 1	cul-de-sac
N = 2	through road
N = 3	equilateral fork
N = 4	cross roads
N = 5	five road junction
N = 6	six road junction

Where n is a real number, the resultant junction will be a hybrid junction.

N = 1.7	skewed through road
N = 2.5	narrow fork
N = 3.5	irregular crossroads

By modifying the equation even further, it is possible to describe all possible road junction configurations, including even variations of road width, for example the case of a minor (narrow) road crossing a major road.

Some variations on the 'platonic junctions' are illustrated below in figure B.3 along with the values of n that generated the graphs. On the following pages are listed some of the modified equations along with the resultant graphs of the junctions types.

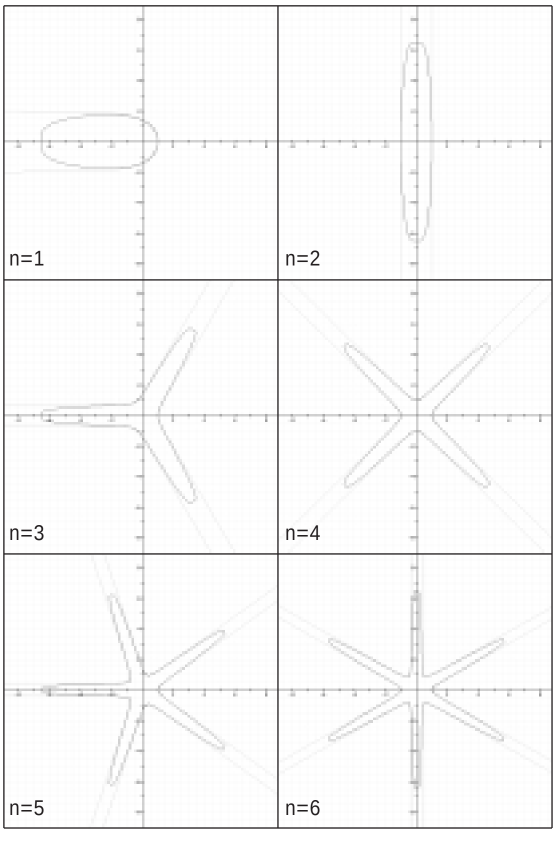

Figure B.9 Platonic Junctions

If the original equation is modified by including a reciprocal of the sine of theta in the same form as the original cosine of theta. The equation used is,

$$r = \left| \frac{2}{(cos(n - 1.5\theta))} \right| + \left| \frac{1}{(sin(n - 0.5\theta))} \right|$$

Equation B.4

When n = zero the junction looks like figure B.10.

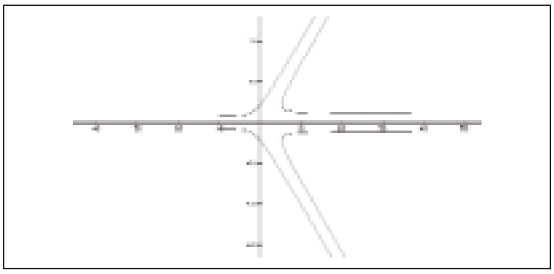

Figure B.10 Equation-generated Psi-junction

This is similar to the Psi-Junction idealised type illustrated at the beginning of the appendix. If, instead of using the value n = 0 the value n = 3.5 is entered into the equation, the resultant junction is a distorted psi-junction, which does not look dissimilar to road junctions found in real-world environments. See figure B.11

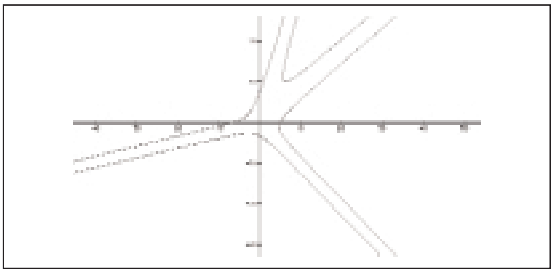

Figure B.11 Equation-generated Distorted Psi-junction

If a different variation of the junction equation is used, for example equation B.5 opposite.

$$r = \left| \frac{3}{(cos(n - \theta))} \right| + \left| \frac{1}{(sin(n - 0.5\theta))} \right|$$

Equation B.5

If the value of n = 0 is entered into the equation the graph resembles a classic T-Junction (figure B.12).

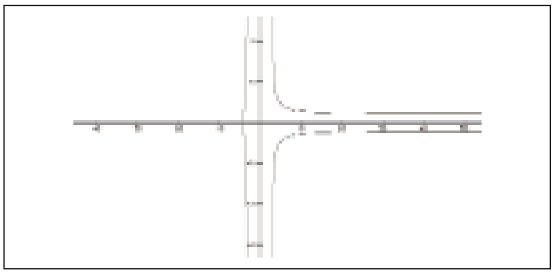

Figure B.12 Equation-generated T-junction

However, if the value n = 1 is used instead then the graph is becomes a side-road forking off a straight through-road, as per the junction type termed asymmetrical fork 2 illustrated at the beginning of the appendix. This junction is shown in figure B.13 below.

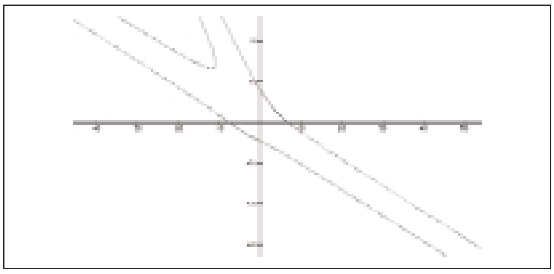

Figure B.13 Equation-generated Distorted T-junction

Another variation of the original equation produces a variation of the width of one of the constituent roads. For example, if equation B.6 below is used,

$$r = \left| \frac{1}{(cos(n - \theta))} \right| + \left| \frac{1}{(sin(n - \theta))} \right| + \left| \frac{4}{(tan(n - \theta))} \right|$$

Equation B.6

By altering the values on the numerators of the equations the road width can be altered accordingly. In the above equation the value of four causes the ‘main road’ to be wider than the ‘side road’. The act of varying n in this equation, alters the rotational angle of the cross-road junction (figure B.14).

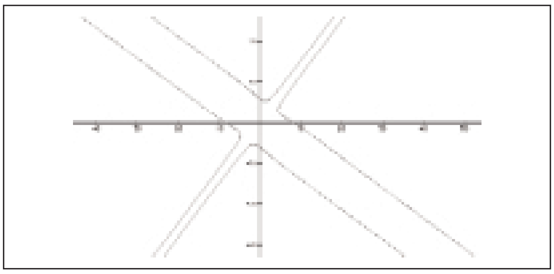

Figure B.14 Equation-generated Main and Side-road Crossroads

One application for being able to describe road junctions through mathematical equations could be the efficient description of urban environments. In order to describe an urban system, it would only be necessary to list the Cartesian co-ordinate of the centre of the junction followed by the polar equation generating the specific junction type. Since the radials are almost parallel, it would be necessary to terminate the roads, as they met another junction. It could be possible to give a precise yet succinct description of an environment in this manner.

Conclusions

This Appendix introduced the idea that since people were pausing at junctions, it may be possible to define a junction in terms of its visual properties. This prompted the proposal of an enlarged typology of road junction types. It has been determined that it is possible to identify road junctions through their isovist attributes. This prompted a question that formed the basis of Chapter 8. If, as it appears, people are pausing at locations where they need to make a route choice decision (usually a junction) then is it possible to correlate people’s pause locations (as calculated in Chapter 7) with isovist attributes? This is the question that was answered in Chapter 8.

Key Points

- Junctions appear to be able to be characterised as areas of high mean isovist radial length (although for certain environments other measures may also be good indicator of junction locations).
- The development of a typology of junction type based on isovist attributes as a valid method of identification can be seen as a fulfilment of Benedikt’s prediction that isovists could be used in this way.
- The use of the mathematical technique known as canonicalisation can be utilised to match any real-world junction to a canonical (or idealised) example.
- Junctions can be described by mathematical equations using polar co-ordinates and based upon variations of the absolute value of the reciprocal of the cosine of theta.

Notes

1 Sonar n. 1 system for the underwater detection of objects by reflected sound. 2 apparatus for this. [SOund Navigation And Ranging]. The device consists of a source of ultrasonic pulses and an electronic circuit to measure the time taken for the pulse to reach the target and its echo to return.

2 The number of points constituting the interval width can be altered. There is no reason that this is five in this example. This could be termed a 5^{th} order moving average.

3 The concept of a Platonic junction is derived from the mathematical concept of a Platonic Solid. Platonic Solids are three-dimensional regular solids created by placing a certain amount of regular polygons around a vertex in three-space. If any randomly selected vertex of a Platonic Solid (of n-sided polygonal faces) were to be held as being the origin of an n-road junction. The layout of the n-road junction could be formed by projecting each edge forming the selected vertex onto a horizontal plane perpendicular to the surface normal at that vertex.

Appendix C: Subject Questionnaires

Bartlett School of Architecture:
Virtual Movement Experiment

The purpose of the following experiment is to determine how we move through virtual space. Over the last twenty years, research at the Bartlett School of Architecture, UCL, has increased our understanding of pedestrian movement through buildings and urban areas (in real space). We now know there to be a very strong relationship between the configuration of physical space (the pattern of spaces; how each distinct space relates to its adjacent spaces, and to the global spatial system). We are now beginning to explore virtual space, and to ask the question; do we use virtual space in a similar way to real space? Can virtual environments be used as architectural research tools?

You will be required to enter an immersive virtual reality and perform a spatial wayfinding task. You will find yourself on the edge of a housing development; the development covers a square area, bounded on all sides by a mixed-use "street". This street represents the limits to your world, and you will not be able to move beyond this "street". Located approximately in the centre of the housing development, there is an open "green" with a monument in the middle. Your task is to find this monument.

This experiment is part of a series of worlds, based on particular spatial theories. This particular world is meant to be confusing and disorientating; it is not inconceivable that you may fail to find the monument, but please do not worry; the results of the experiment are not dependent on your successful completion of the task. Throughout the experiment your movements and choice of routes in the virtual environment will be recorded. The following experiment should last no longer than 10-15 minutes. If at any point; for any reason you wish to terminate the experiment, please indicate your wishes, and the experiment will cease.

Please take time to complete the following questionnaire, ticking boxes ❑ ✔ where appropriate.

Personal Information

Name ________________________________Age ________ Occupation ______________

Male ❑ Female ❑

Left handed ❑ Right handed ❑ Ambidextrous ❑

Long sighted ❑ Short sighted ❑ No known ocular abnormalities ❑
Other ❑

Please tick which one of the following statements best describes your previous experience of virtual environments;

a) This is my first time in an immersive virtual environment ❑

b) I have some (but limited) experience of virtual environments ❑

c) I regularly experience virtual environments but do not feel fully familiar with the technology ❑

d) I frequently experience virtual environments, and feel familiar with the technology ❑

e) If none of the above statements adequately describe your level of experience, tick this option and/or write your own statement in the space below ❑

____

Figure C.1 Page One of Questionnaire Used in ICA Experiment (World B)

The Experiment

The following section must be completed after you have participated in the experiment.

1. Did you feel any physical sensations such as dizziness or nausea?

Yes ❑ No ❑ If "yes" please describe your sensations

____

2. How "real" did the environment feel to you?

I felt I was really there ❑ I was constantly aware of being in a virtual environment ❑

None of these ❑

3. Did you feel any emotions such as frustration, disorientation etc.?

Yes ❑ No ❑ If "yes" please describe your emotions

____

4. Did you attempt to employ any strategy in order to find the monument (i.e. alternate between left and then right turns)?

Yes ❑ No ❑ If "yes" please describe your strategy

____

____

5. The housing development was composed of standard urban "blocks" There were two types of "blocks". Can you draw these two types of urban block in the space below and left?

6. On the map below and to the right, can you sketch on the map the approximate route you "think" you took to the "green"?

Please draw your impression of the urban "blocks" in this space

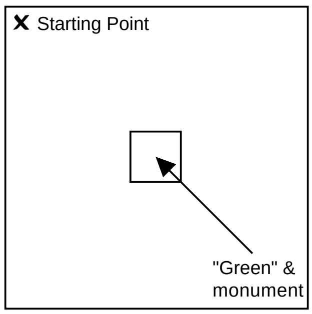

Figure C.2 Page Two of Questionnaire Used in ICA Experiment (World B)

Bartlett School of Architecture:
Virtual Movement Experiment

Subject Number ________________

The purpose of the following experiment is to determine how we move through virtual space. Over the last twenty years, research at the Bartlett School of Architecture, UCL, has increased our understanding of pedestrian movement through buildings and urban areas (in real space). We now know there to be a very strong relationship between the configuration of physical space (the pattern of spaces; how each distinct space relates to its adjacent spaces, and to the global spatial system). We are now beginning to explore virtual space, and to ask the question; do we use virtual space in a similar way to real space? Can virtual environments be used as architectural research tools?

You will be required to enter a series of immersive virtual worlds and perform a couple of different tasks.

<u>Worlds 1 & 2</u>

These are a pair of theoretical worlds, constructed with the same “set” of buildings, but with each environment arranged slightly differently. You are required to perform a spatial wayfinding task. In each world, directly ahead of you (in the direction you are facing, when you appear in the world) there is an open Market Square with a monument at its centre. You are to attempt to locate this monument. After you have found it you may continue to explore the world, if you wish.

You will be unable to walk through the buildings, as solidity has been implemented in these worlds, try not to ”skim” any corners, since it is possible to get “stuck”. If you navigate “generously” around the corners, you should avoid this problem.

<u>Worlds 3 & 4</u>

These are a pair of theoretical worlds, constructed with different buildings block types and arrangements. The tasks in these worlds are simply to explore, to “wander at will”.

You will be unable to walk through the buildings, as solidity has been implemented in these worlds, try not to ”skim” any corners, since it is possible to get “stuck”. If you navigate “generously” around the corners, you should avoid this problem.

<u>World 5</u>

This is a simulation of a real part of London. You will be given a series of sequential wayfinding tasks to perform.

In this particular environment, there is no solidity. Please try to avoid walking through any of the buildings, since this would nullify the experiment. If you come to the edge of the built environment, please turn back and continue navigating through the environment, rather than moving around the edge of simulation.

Figure C.3 Page One of Questionnaire Used in Experiments (World C-G)

General notes

The results of the experiment are not dependent on your successful completion of the task. Throughout the experiment your movements and choice of routes in the virtual environment will be recorded.

Each experiment will last no longer than 10 minutes. If at any point; for any reason you wish to terminate the experiment, please indicate your wishes, and the experiment will cease.

Please take time to complete the following questionnaire, ticking boxes ❑ ✔ where appropriate.

Personal Information

Name ________________________________Age ________ Occupation ______________

Male ❑ Female ❑

Physical Characteristics

Left handed ❑ Right handed ❑ Ambidextrous ❑

Long sighted ❑ Short sighted ❑ No ocular abnormalities ❑ Other ❑

Please tick which one of the following statements best describes your previous experience of virtual environments;

a) This is my first time in an immersive virtual environment ❑

b) I have some (but limited) experience of virtual environments ❑

c) I regularly experience virtual environments but do not feel fully familiar with the technology ❑

d) I frequently experience virtual environments, and feel familiar with the technology ❑

e) If none of the above statements adequately describe your level of experience, tick this option and/or write your own statement in the space below ❑

Have you played computer games, such as Quake/Doom or TombRaider Before? Yes ❑ No ❑

If the answer to the question above is yes, then what games do you play regularly?
____

Figure C.4 Page Two of Questionnaire Used in Experiments (World C-G)

The Experiment

The following section must be completed after you have participated in the experiment.

1 Did you feel any physical sensations such as dizziness or nausea?

Yes ❑ No ❑ If "yes" please describe your sensations ______________________________

____
____
____
____

2 How "real" did the environment feel to you?

I felt I was really there ❑ I was constantly aware of being in a virtual environment ❑

Neither of the above ❑

____
____

3 Did you feel any emotions such as frustration, disorientation etc.?

Yes ❑ No ❑ If "yes" please describe your emotions _______________________________

____
____
____
____

4 Did you attempt to employ any strategy in order to find the monument?

Yes ❑ No ❑ If "yes" please describe your strategy ________________________________

____
____
____
____
____
____

5 Any other comments or observations?

____
____
____
____
____

Figure C.5 Page Three of Questionnaire Used in Experiments (World C-G)