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.

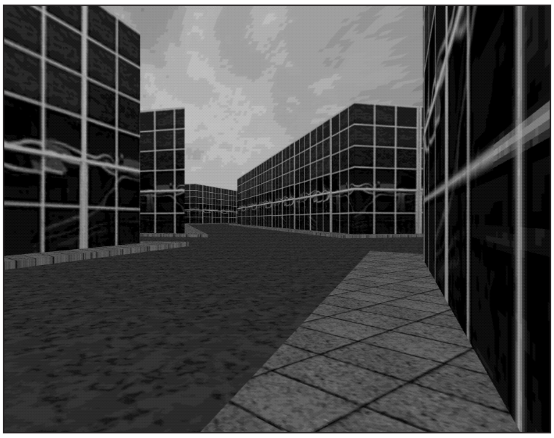

Figure 6.1 Screenshot of World E

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.

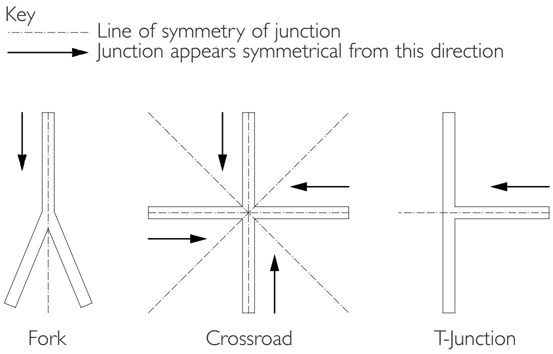

Figure 6.2 Symmetry of Junction Types

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).

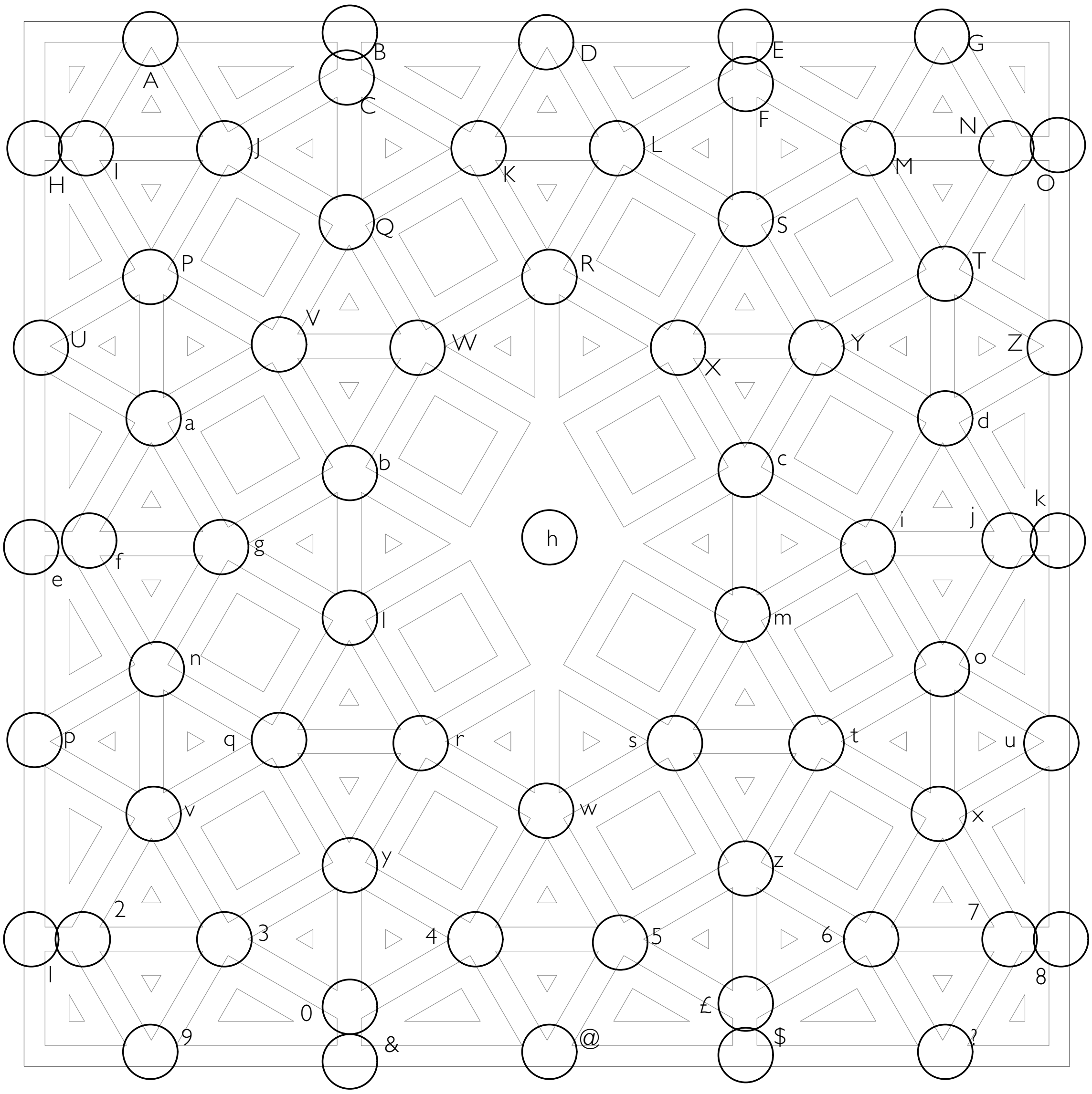

Figure 6.3 Identification of Road Junctions

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

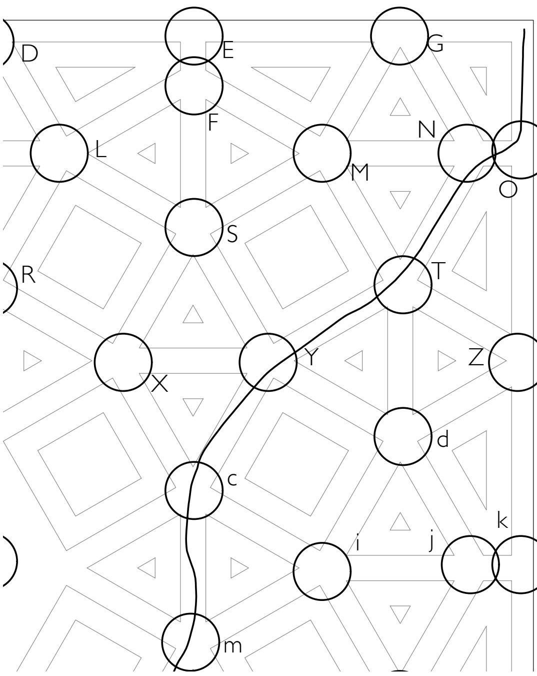

Figure 6.4 Portion of a Journey through World E

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.

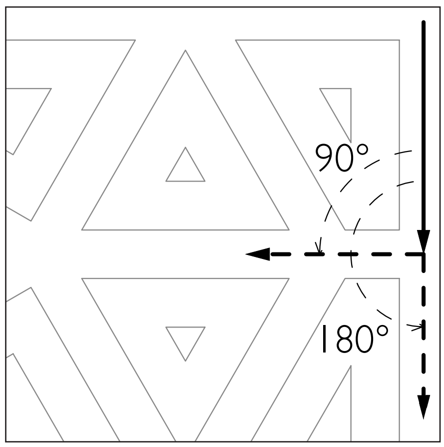

Figure 6.5 Available Route Choices at Node "O"

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.

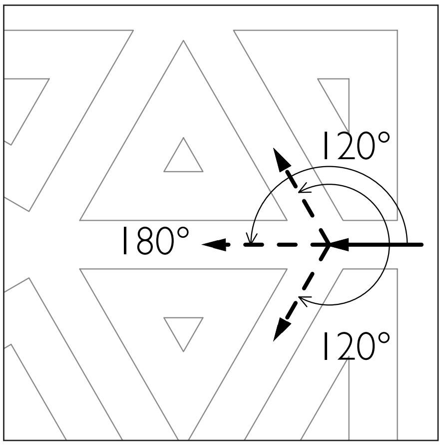

Figure 6.6 Available Route Choices at Node "N"

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

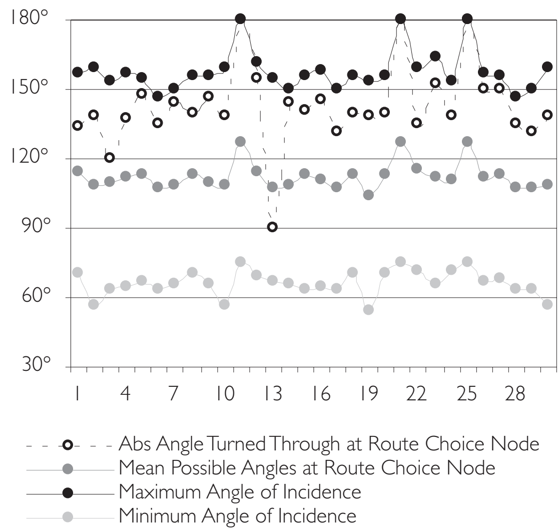

Figure 6.7 Graph of Minimum, Mean and Maximum Angles Turned through in all Routes

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

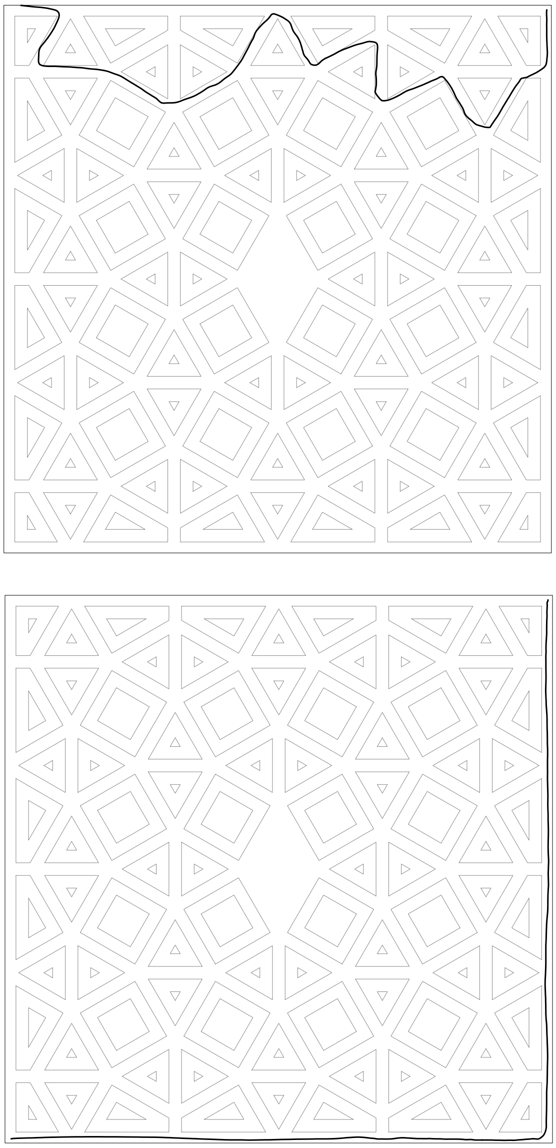

Figure 6.8 The Straightest and Least Straight Routes in the Sample

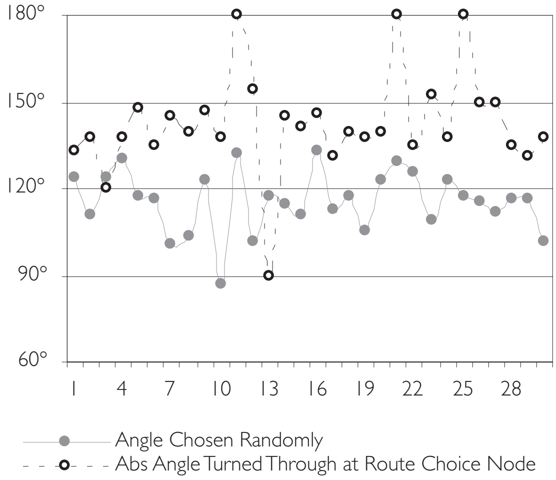

Figure 6.9 Graph Comparing Choices made by Subjects to Random Route Choices

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

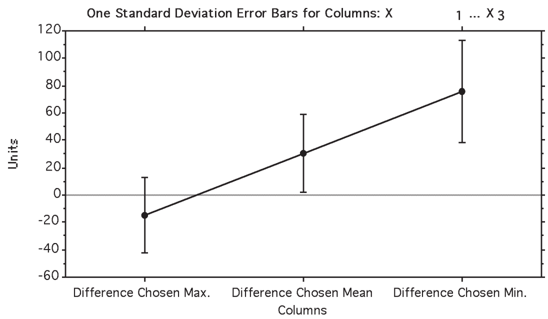

Figure 6.10 Standard Deviation Error Bars

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

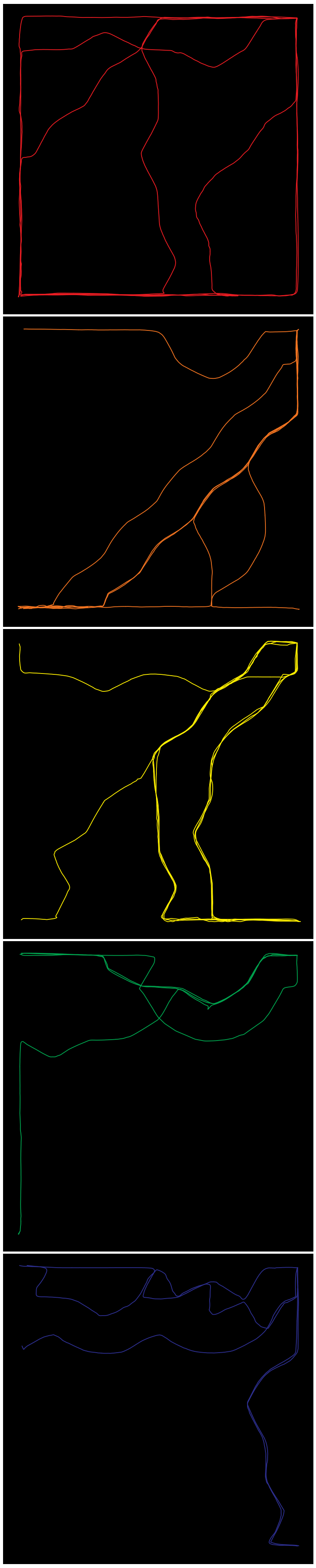

Figure 6.11 Routes Coloured by Mean Journey Angle

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 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.

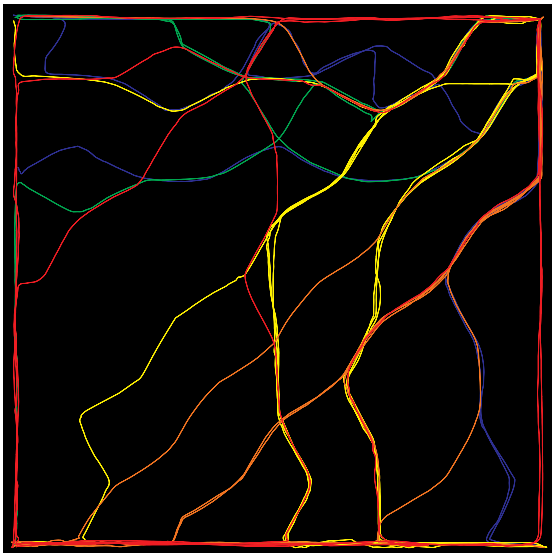

Figure 6.12 All Routes Coloured by Mean Journey Angle

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.

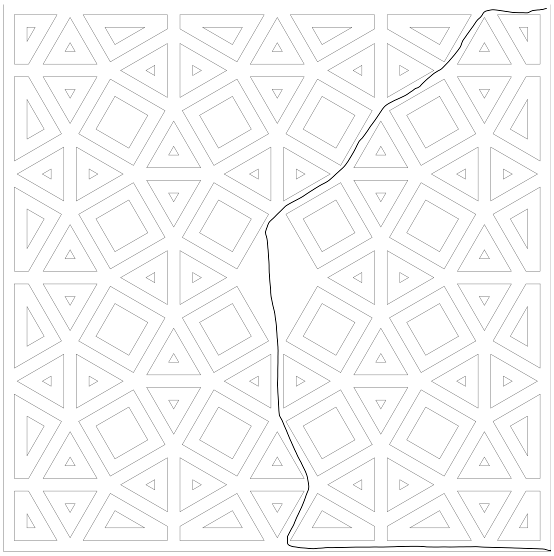

Figure 6.13 Example Route through World E

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

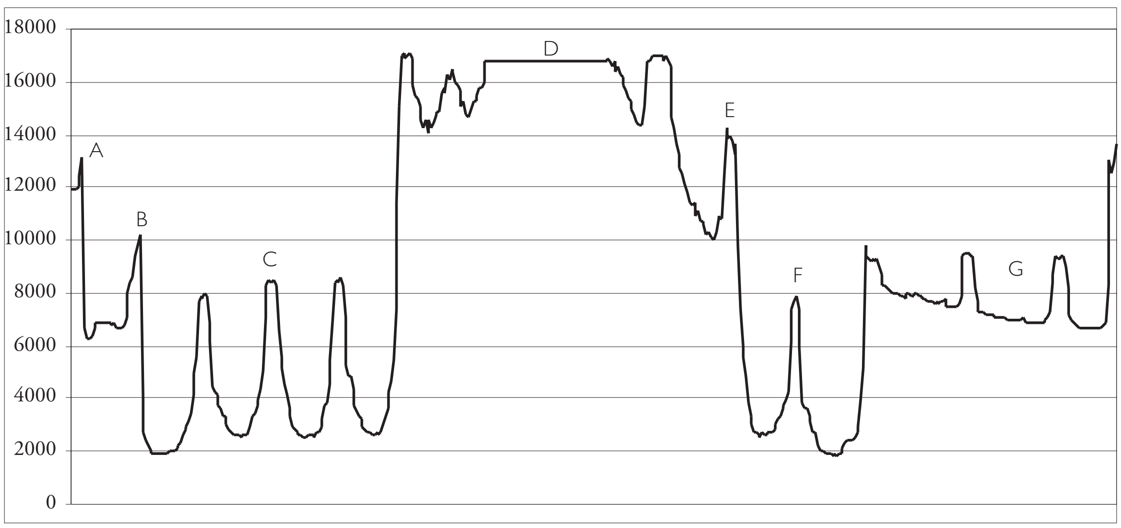

Figure 6.14 Route Vision Profile for the Isovist Attribute Area

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

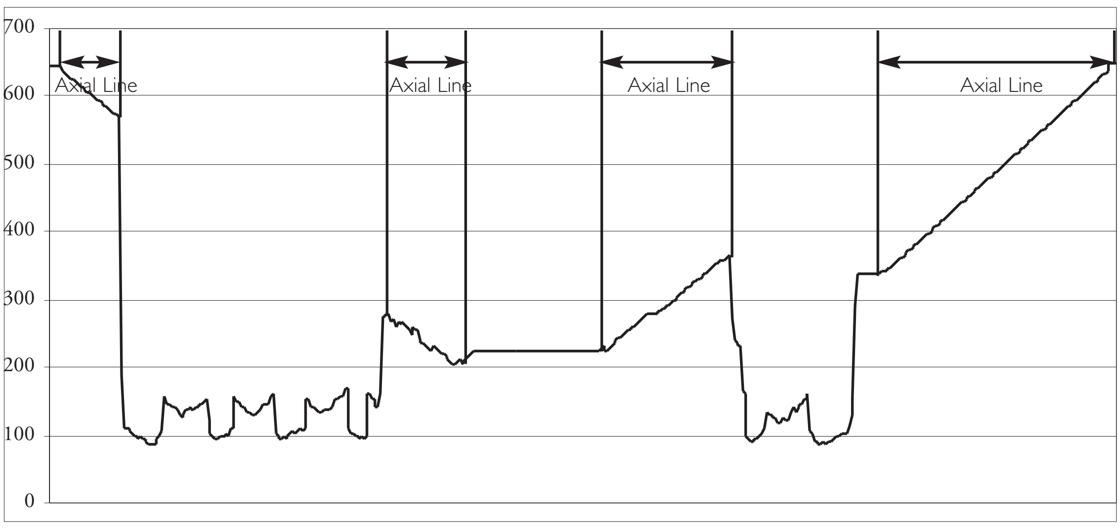

Figure 6.15 Route Vision Profile for the Isovist Attribute Maximum Radial Length

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

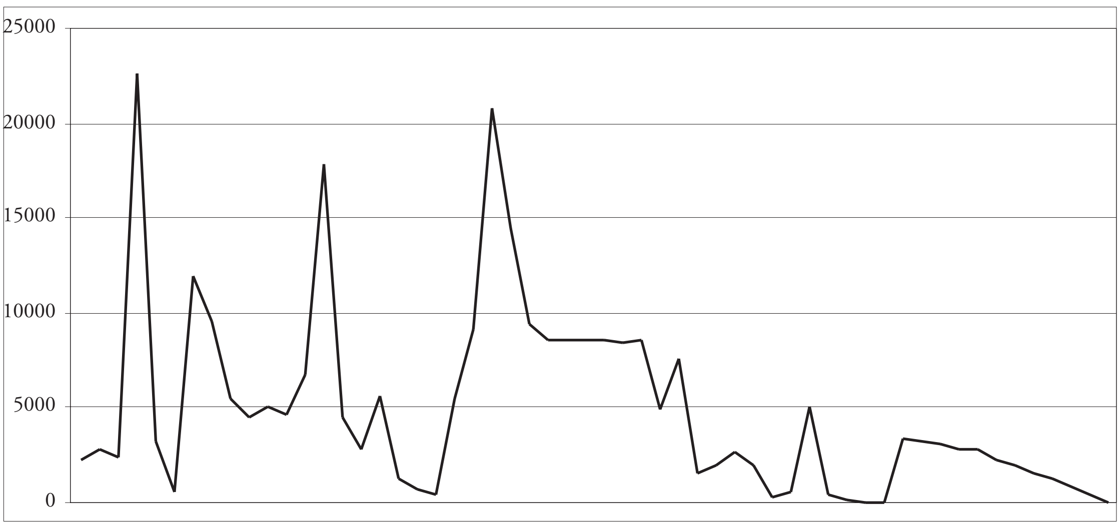

Figure 6.16 Route Vision Profile for the Isovist Attribute Area (Restricted FOV)

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.