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Location: **Periodicals**

Journal Title: Environment and planning. B, Planning & design.

Volume: 35 **Issue:** 5
Month/Year: 2008**Pages:** 881 – 901

Article Author: Peponis, John; Bafna,Sonit; Zhang, Zongyu

Article Title: The connectivity of streets; reach and directional distance

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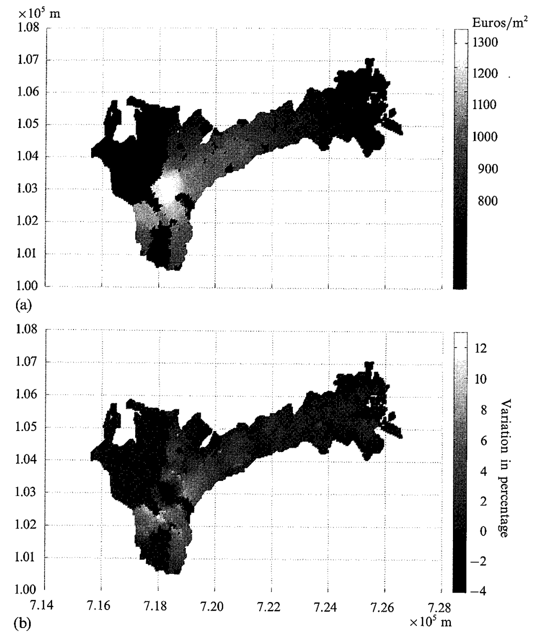

Figure 5. [In color online.] (a) The spatial distribution of the real estate value measured in euros per square meter. The plotted quantities are mean values in circular neighbourhoods with a radius of 150 m surrounding each cadastral parcel. (b) The relative variation in percentage values, with respect to the initial configuration. The axes are labelled using the Swiss national coordinate system.

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Environment and Planning B: Planning and Design 2008, volume 35, pages 881 – 901

doi:10.1068/b33088

The connectivity of streets: reach and directional distance

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Received 26 July 2006; in revised form 3 April 2007

Abstract. We introduce two measures of connectivity that are applicable to standard GIS-based representations of street networks. The *reach* of a point measures the total street length covered by all paths extending out from that point that are no longer than a given threshold value. The *directional distance* of a street network from a point is measured according to the minimum number of direction changes required to reach any part of the network from that point, consistent with typical measures used in space syntax. However, our measure of directional distance requires no prior commitment as to the relational elements that make up the network. Any part of the network which is accessible from a point without a change of direction greater than a given threshold angle is treated as a single directional element for the purposes of computation. Street segments are characterized by the reach and directional distance of their midpoints. Networks are characterized by the average directional distance of the corresponding street segments. The measures render explicit the interplay between metric and topological properties of networks. Preliminary studies show that the measures discriminate well between different morphologies of street networks. When used to compare urban morphologies they are well correlated with standard measures used in the literature, with the added advantage that they can discriminate between street segments within the same urban area. Using field observations we also show that the measures can be used to model the effect of spatial configuration upon movement in ways which compare favorably to standard space syntax.

Introduction

In the most general sense, connectivity is about relatedness. In this paper we discuss the specific form of relatedness that arises according to the structure of street networks. We do not limit the idea of connectivity to some local measure, such as the number of intersections along a street, or the number of streets that come together at an intersection; these are best denoted by the term 'degree', as it pertains to the node of a graph representing relationships between elements. The aims of this paper are twofold. First, to introduce measures of street connectivity that can be computed on the basis of standard GIS representations of street networks, such as the street centerline maps that are readily available for all cities in the US. Second, to rethink some of the measures of street connectivity associated with space syntax in a way which takes into account recent advances in the field, as well as criticisms raised by authors who have discussed space syntax in this journal in recent years. In addressing these aims we set the foundations for future research aimed at testing theoretical hypotheses. This paper is focused upon the definition and clarification of descriptive concepts and their computational implications. Still, we present the results of a pilot field study indicating that the new measures postdict the distribution of pedestrian movement as well as standard syntactic measures. We also discuss the relationship of the new measures to standard morphological measures used in the literature.

Preliminary definitions

We define below the main elements used in the analytical framework, consistent with the way in which street networks are depicted in most GIS databases in the US. Streets, including curvilinear streets, are represented as chains of simple straight-line segments. All street intersections are defined as end points of line segments. Given this format, we will use the term 'road node' to refer to a street intersection at which there is a choice of paths, or to the end-point of a line that marks a dead-end street; we will use the term 'line node' to refer to the common point at which two consecutive line segments meet exactly. Similarly, we will use the term 'line segment' to refer to the actual straight lines that constitute the database, and the term 'road segment' to refer to a chain of straight lines that lie between two road nodes. It follows that a road segment may consist of one or more line segments.

Since they extend between road intersections at which we have a choice of divergent paths, road segments have an obvious experiential foundation. They also have a secondary experiential correlate which is perhaps less obvious: traditionally, we define an urban block face as the part of the perimeter of a block that extends between two road intersections; road segments are, therefore, associated with block faces on one or both their sides, depending on the degree of the intersections involved. Figure 1 clarifies the difference between line segments and road segments.

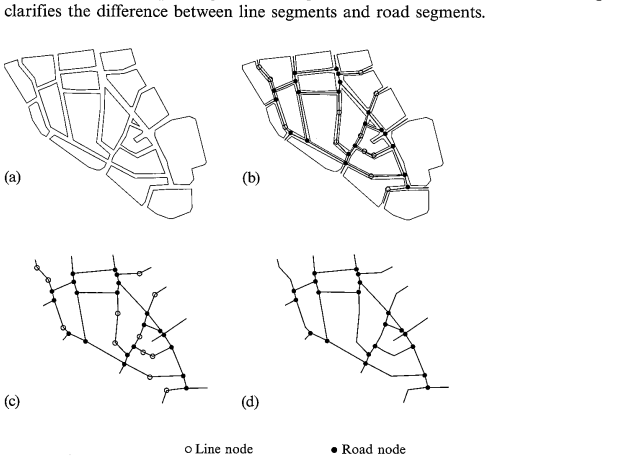


Figure 1. Representations of a street network, consisting of line segments joined at line nodes and road segments that lie between road nodes. (a) Urban area; (b) network of streets over area map; (c) line segments; (d) road segments.

Metric reach: a measure of potentiality and density

The sense of *potential* is fundamental to our conception of urban street networks. Streets provide a framework for at last four kinds of movement: first, routine movement from familiar origins to familiar destinations, such as the daily route from home to work; second, new path-making to particular but previously unvisited destinations, such as the home of a new acquaintance that has invited us for dinner;

third, meandering movement within a relatively known area, as when we take a stroll with a friend; fourth, exploratory movement aimed at understanding a new environment, such as we engage when visiting a city for the first time. In everyday life the four kinds of movement merge, as when we deviate from a routine path in order to check whether the surrounding area offers opportunities for convenient shopping. The density of streets over a given area affects the potential for these kinds of movement within reasonable ranges of walking distance. The denser the street network, for example, the greater the number of destinations we can reach when we walk and the greater the chances that we can discover new places in otherwise familiar neighborhoods.

We propose to measure the potential offered by a network of streets by asking a very simple question: how much street length can be reached as we walk in all possible directions from a given origin up to a certain distance threshold? Supposing that we walk 1 km within 10 minutes, we may, for example, ask how many kilometers of street are potentially available within 10 minutes walk from a given origin, by setting the distance threshold to 1 km.

The idea of metric reach is illustrated in figure 2, which also clarifies that we are dealing with parts of streets constituting continuous physical paths, rather than with parts of streets included in a circle of a given radius.

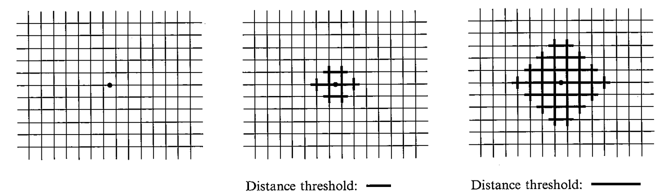


Figure 2. A diagrammatic definition of metric reach.

Formal definition of metric reach

We define a path $p(ij\text{-}s)$ as a nonbranching sequence of road segments and fractions of road segments that has a point P_i as its origin, point P_j as its end, and an aggregate length s; typically, the first interval of a path will be a fraction of a road segment, because P_i will not coincide with a node; the last segment will also be a fraction of a road segment, depending of the length of the path.

We define the *metric reach* $R_v(P_i, \mu)$ of a point P_i according to a metric threshold μ as the length of the road segments and fractions of road segments covered by the union of all paths for which $s \leqslant \mu$; of course, no line segment or fraction of line segment is counted twice.

In developing the algorithm for the computation of metric reach we consider Dijkstra shortest-path trees of the dual graph of the usual node–link representation used in GIS, such that weighted nodes represent road segments with assigned metric lengths. However, metric reach is not equivalent to the minimum spanning tree from a given point up to a given distance because we consider fractions of road segments and not only complete road segments.

The average metric reach of street networks and subsets of street networks

In order to characterize urban areas according to mean metric reach $[\bar{R}_v(P_i, \mu)]$ we proceed to compute $R_v(P_i, \mu)$ from the midpoint of every road segment within the given area, and to characterize an area by the mean $\bar{R}_v(P_i, \mu)$ value of all the road

Table 1. Numeric description of urban areas in the Atlanta Regional Commission.

2 mile × 2 mile area (4 mile^2; 10.4 km^2)	$\bar{R}_v(P_i, 1\text{ mile})$ (in miles)	$\bar{D}_v(P_i, 1\text{ mile})$ (in miles)
Alpharetta	12.93	6.96
Ansley Park	27.87	4.37
Avondale	20.05	6.46
Brookhaven	18.78	6.44
Buckhead	20.84	4.93
Candler Park	29.96	3.70
College Park	32.81	3.22
Crabapple	9.46	9.50
Decatur	26.80	5.45
Downtown	53.24	3.23
Dunwoody	13.05	8.80
Fairburn	17.73	3.99
Fayetteville	15.29	6.75
Forest Park	25.27	4.71
Lawrenceville	19.47	5.03
Marietta	32.52	4.46
Norcross	14.72	6.02
Oakgrove	16.23	7.45
Peachtree City	14.88	7.63
Roswell	16.49	5.44
Smyma	22.49	5.59
Stone Mountain	18.45	6.27
Union City	15.95	6.35
Virginia Highland	26.16	4.74
West End	31.39	3.57
Average for area of Atlanta Regional Commission (2981 mile^2, 7721 km^2)	13.58	7.22

segments in it. Thus defined, the mean metric reach of an area is also a measure of density. It measures the density of available streets. Table 1, column 2, for example, presents the mean metric reach values of different 2 mile × 2 mile areas within the larger area of the Atlanta Regional Commission, shown in figure 3. The mean metric reach values clearly show that the older cities (Atlanta, Marietta, Decatur, College Park) and early suburbs (Ansley Park, Virginia Highland), have denser networks than the emerging commercial and business centers (Dunwoody-Perimeter Mall) and the outlying areas (Crabapple, Peachtree City). New urban centers with unevenly distributed densities of development (Buckhead) appear to evolve on the basis of street networks approximating the density of early suburbs.

The question arises as to how powerful the mean metric reach is as a descriptor of urban areas. At this point, comparisons between mean metric reach and other measures commonly found in the literature become relevant. Some authors, for example, have suggested that the total street length, the number of street intersections, and the number of blocks by unit area are good measures of urban street patterns (Jacobs, 1996; Siksna, 1997; Southworth and Owens, 1993). From a mathematical point of view the mean metric reach of an area is not equivalent to any of these measures. We can easily construct theoretical layouts such that areas with the same street length, or the same street length and number of intersections, or the same number of blocks, have different mean metric reach values, as shown in figure 4.

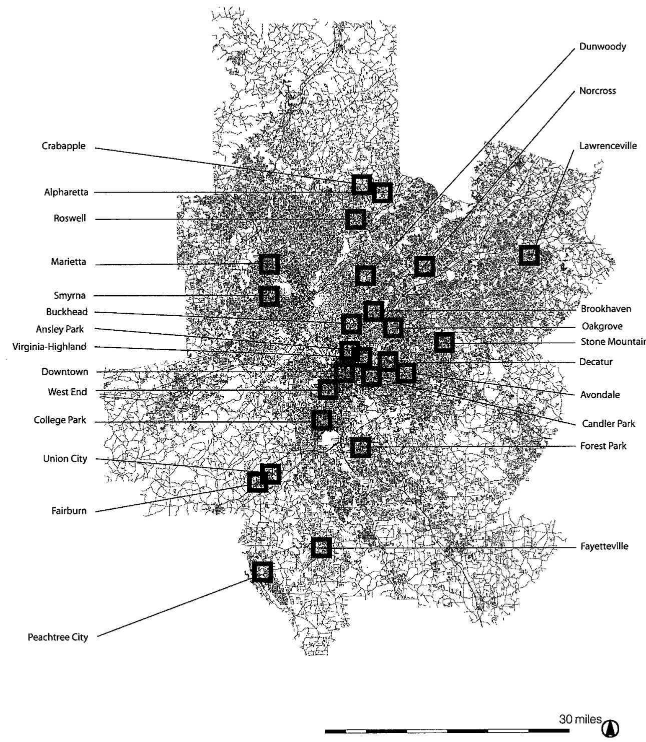


Figure 3. A sample of 2 mile × 2 mile urban subareas in the area covered by the Atlanta Regional Commission.

However, we have pursued the relationship between mean metric reach and other measures in two ways. First, we studied the relationship between block size and mean metric reach in theoretical infinite regular square grids, as shown in figure 5. For such grids, the smaller the urban blocks, the higher the mean metric reach. Furthermore, the smaller the block size, the higher the rate at which the metric reach increases with an increase in threshold distance. Based on these mathematical trends, the graph shown in figure 5 can also function as a heuristic comparative yardstick: for a given threshold distance, we can ask which regular grid dimension would produce the mean reach value empirically found in an actual urban area. For example, the mean metric metric reach with a 1 mile distance threshold for some of the sparse exurbs surrounding Atlanta corresponds to the value that would be obtained for a square grid of a 1640 ft (500 m) module.

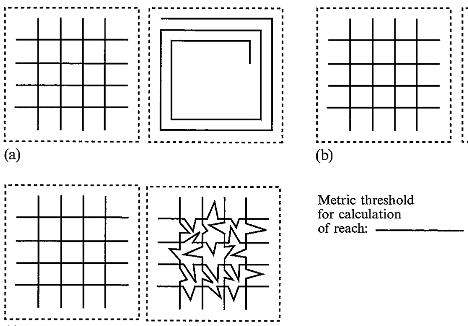


Figure 4. A demonstration that mean metric reach is not mathematically equivalent to street length, number of intersections, or number of blocks by unit area. (a) Same street length; (b) same street length and same number of intersections; (c) same number of blocks and same number of intersections. In each case the left figure has a higher mean metric reach and the right figure has a lower mean metric reach.

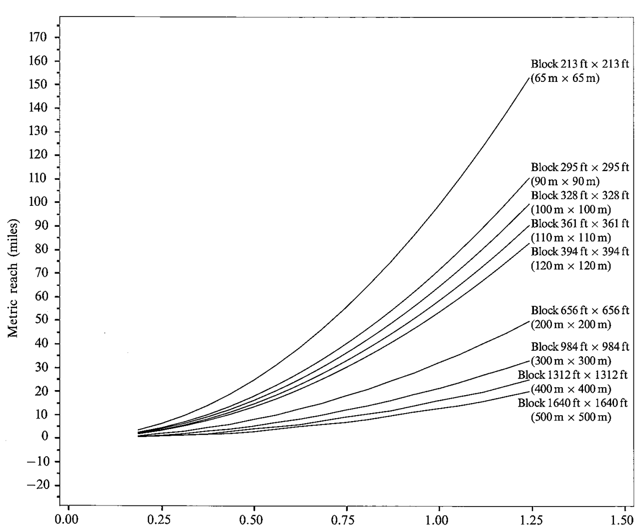


Figure 5. A plot of the relationship between metric reach values and block sizes in infinite square grids.

Working with our colleague Martin Scoppa, we examined further the relationship between metric reach, street length per area, the number of blocks per area, and the number of intersections per area in a sample of urban areas drawn from the larger area of the Atlanta Regional Commission. For the sake of exploring the correlation between these measures, we considered each of the twenty-five areas as an island—that is, in isolation from its urban surroundings. Each sample area was initially chosen using a 2 mile × 2 mile square boundary, similar to the one used in figure 3. However, the increasing size of urban blocks as we move to the exurbs of Atlanta required us to develop a strategy for augmenting the area under consideration in order to be consistent regarding the number of blocks included in the calculation. Thus, we extended each initial 2 mile × 2 mile area as needed, in order to cover not only all blocks entirely contained within the 2 × 2 boundary, but also all those intersected by it. Similarly, we extended the street system in order to entirely surround these blocks. Our measures are thus based on areas of unequal size, as shown in table 2. We also note that, consistent with Southworth and Owens (1993), we only counted street intersections associated with a choice of extended paths. Finally, we warn the reader that discrepancies between metric reach values offered in table 2 and values offered in table 1 are due to two facts: first, the areas are considered in isolation in table 2 but as parts of the larger system in table 1; second, the areas in table 1 are wholly contained within a 2 mile × 2 mile square, whereas the areas in table 2 are extended to include all blocks intersected as well as wholly contained by the 2 mile × 2 mile square. These differences correspond to different research intents. Table 1 is aimed at characterizing

Table 2. Metric reach, and block, linear street length, and intersection densities in twenty-five areas in Atlanta.

Area	Acres	$\bar{R}_v(P_i, 1\text{ mile})$ (in miles)	Blocks/mile^2	Street length/mile^2 (in miles)	Intersections/mile^2
Alpharetta	5167.2	9.90	19.1	11.5	65.1
Ansley Park	4164.5	18.30	40.1	15.5	93.9
Avondale	3534.7	14.38	30.2	15.2	80.4
Brookhaven	4510.1	13.73	23.7	12.8	69.8
Buckhead	3904.8	14.84	26.4	13.9	69.2
Candler Park	3203.9	21.43	54.3	18.3	118.3
College Park	3579.8	25.68	67.9	18.1	121.4
Crabapple	6726.6	6.51	6.0	8.2	40.2
Decatur	3534.2	20.53	39.3	15.9	96.9
Downtown	2923.4	39.78	151.5	26.7	234.0
Dunwoody	3499.2	9.66	20.7	14.0	67.1
Fairburn	6744.9	12.75	10.7	8.0	30.8
Fayetteville	9268.2	9.96	9.4	8.5	37.4
Forest Park	4308.0	19.26	32.1	15.1	86.3
Lawrenceville	6734.3	12.73	16.0	10.6	53.4
Marietta	3865.7	25.98	53.6	16.9	114.9
Norcross	5315.4	10.76	14.1	11.1	50.8
Oakgrove	4373.2	11.97	17.7	14.2	72.0
Peachtree City	6285.7	10.41	14.5	10.5	51.7
Roswell	5499.2	11.43	17.0	11.6	61.9
Smyma	3672.1	16.91	38.5	16.9	108.8
Stone Mountain	5082.1	14.18	17.8	11.1	55.7
Union City	6017.6	12.18	11.4	7.9	36.1
Virginia Highland	4204.8	19.01	34.6	14.4	82.3
West End	3307.4	22.07	61.9	19.8	127.9

metrically equivalent parts of the region of Atlanta; table 2 is aimed at providing us with experimental data in order to study the covariance of descriptive variables.

On the basis of table 2 we found that the number of blocks per square mile accounts for 90% of the variance in mean metric reach ($R^2 = 0.905$, $p = 0.0001$). The correlation between mean metric reach and the number of intersections per square mile is almost as strong ($R^2 = 0.872$, $p = 0.0001$); the correlation between mean reach and the street length per square mile is somehow weaker ($R^2 = 0.795$, $p = 0.0001$). Quite clearly, while mean metric reach is not mathematically—that is, necessarily—associated with the other three measures considered here, it is empirically found to be strongly associated with them. Why should we be interested in metric reach if that is the case? Why not characterize the difference between areas using the standard spatial density measures available in the literature?

The answer to this question is both simple and fundamental to a morphological theory of space. The other measures that we compare with metric reach can only characterize an area in aggregate. No specific values can be assigned to a single street or urban block. By contrast, metric reach varies per road segment. Thus, it is possible to characterize not only specific streets or parts of streets, but also specific block faces according to the streets they front on. Thus, metric reach lends itself not only to an aggregate description of an area but also to a differentiated description of its various parts. This is due to the fact that metric reach is a relational measure describing connectivity, not a simple count of the elements that make up an area. We conclude that metric reach adds information when used in conjunction with other measures of street density found in the literature, while being an indispensable measure when we study phenomena for which the street segment rather than the area is the appropriate unit of analysis.

Directional distance

When we engage in routine movement it is likely that the paths we choose are economic with respect to factors such as time, distance, physical or cognitive effort, or ability to connect multiple destinations. Similarly, when we engage in exploratory movement of different kinds it is unlikely that all paths available within a given metric range are treated as equivalent choices. Our everyday sense of urban space suggests that potential—that is, the availability of accessible streets and accessible destinations—is complemented by structure, the ordering of accessible streets and destinations in some way that informs our navigation choices. There is good evidence, as indicated below, that directional distance is important to the structure of street networks, influencing why some streets are more likely to be used than others, either for routine or for exploratory movement. Simply defined, directional distance is not measured in units of length, but rather in direction changes. This is illustrated in figure 6. Figure 6(a) shows the set of spaces associated with the metric reach of a point on a partially deformed grid. Figures 6(b) and 6(c) show the subsets of this set which comprise only those spaces which can be reached with up to a given number of direction changes. Because of the deformation of the grid, the area to the left of the origin is directionally more easily accessible than the area to the right, even though the metric distances are roughly equivalent.

This assumption that directional distances introduce a cognitively and functionally relevant structuring order to accessible streets takes into account research findings from a variety of sources. Some sources bear on spatial cognition and behaviors closely associated with spatial cognition. Based on research in cognitive neuroscience, there is evidence that direction turns play a very important and independent role in determining navigation efforts as measured by the time taken to complete a path in a maze, over and

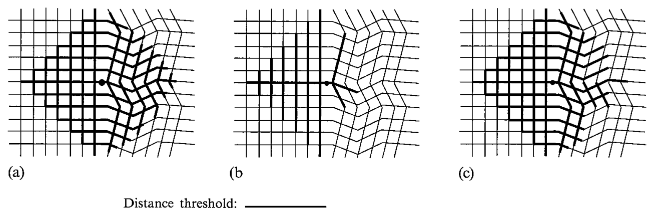


Figure 6. The directional orders within the metric reach of a point. (a) Metric reach; (b) street sections within one direction change; (c) street sections within three direction changes.

above the effect of total path length (Crowe et al, 2000). Similarly, based on research in environmental psychology, there is evidence that direction changes, as an aspect of configurational complexity, hinder wayfinding ease (Moeser, 1988; O'Neill, 1991). There is further evidence that the number of direction changes influences the estimation of metric route length (Sadalla and Magel, 1980), even though more recent research suggests that the effect is more evident when the same subject estimates routes with different numbers of turns (Jansen-Osman and Wiedenbauer, 2004). There is also evidence that the number of turns increases the cognitive load on memory; Montello (1991, pages 59–60) reports that subjects asked to point to not-visible landmarks required a greater response time if they were situated on a street that is two turns away from the main grid, in comparison with those subjects who were situated on streets only one turn away. Finally, there is evidence that preferred paths between two points on a map are those that include fewer turns overall (Bailenson et al, 2000) and also those that include a long relatively straight segment right at the beginning (Bailenson et al, 1998). Taken together, these studies show that direction changes have a significant and detectable impact on spatial cognition.

Empirical studies associated with space syntax have also demonstrated that street lines which are accessible from the surrounding network with fewer direction changes tend to be associated with higher densities of pedestrian movement (Hillier et al, 1987; 1993; Peponis et al, 1989). In a recent paper, Hillier and Iida (2005) argued, based on a more extensive analysis of how movement data correlate to a range of spatial variables, that accessibility measured by direction changes is a good predictor of movement because it captures something about the manner in which people understand street networks. The idea that the ordering of street lines according to directional accessibility has cognitive import is also supported by findings that more directionally accessible street lines feature more prominently in cognitive maps of urban areas (Kim and Penn, 2003). It is further supported by findings that directional accessibility plays a significant role in determining the paths taken by people who explore unfamiliar environments, or seek to find particular destinations in unfamiliar environments (Haq, 2003; Peponis et al, 1990), as well as by the finding that people crossing an area tend to use the path involving fewer directional changes (Conroy Dalton, 2003).

If we accept directional distance to be important to the way in which people move through and understand the structure of street networks, how do we measure it? There are two basic questions involved before we even start the analysis. The first concerns the fundamental unit of analysis. The second concerns the magnitude of direction change over any given path. We want to address these two questions with particular reference to space syntax.

Direction changes and directional elements

The fundamental representation used for the syntactic analysis of street networks is the 'line', or 'axial' map, which comprises the fewest and longest lines which are necessary in order to get everywhere and complete all possible circulation loops (Batty and Rana, 2004; Hillier and Hanson, 1984; Peponis et al, 1998; Turner et al, 2005). The lines of the line map can be shorter than the face of a curvilinear block or very long, depending on the geometry of streets. The line map is essentially used in order to allow the computation of directional distance between different locations in the urban area represented. But the technique, in addition, also allows a generic definition of 'all' potential locations in the urban system. From the point of view of directional distance, any location on a line—or more accurately, any location in a street represented by a line—is undifferentiated from any other. Thus, the directional distance between two locations in the urban area can be effectively reduced to the directional distance between lines associated with them. It is also worth noting that the directional distance between two lines is measured in units of lines traversed in moving from one to another: if a line intersects another directly, it is at a distance of one step from that line, and every line intersecting it in the chain adds a unit distance to the original line. The distances from a line to a set of lines can be assigned as a value to the line in question. Thus, the characteristics of an entire urban area associated with directional distances can be completely described in terms of the direct relations amongst a finite, even if very large, number of lines. The lines, therefore, are both units of analysis and units of computation. The fact that a representation as simplified as the line map has proved so robust and fruitful in the analysis of street networks is to some extent a puzzle that calls for further research into spatial cognition.

Be that as it may, the axial line as a unit of analysis has drawn several kinds of criticism. The first criticism is that very long lines do not correspond to perceptually available units of space, even less so when they cross significant grade changes (Steadman, 2004). The second criticism is that, by using the axial line as a unit of analysis, we cannot interpret differences which arise along its length, whether to do with the density of intersections (Hillier, 1999a), or the density of movement—a problem which would not arise with the node-link representations which are typical in GIS.

We will formally define directional distances in a way which does not evoke the line map. This is partly in response to these criticisms and partly in response to the format in which data are given in GIS databases. Our measure of directional distance will not assume any fixed directional elements. Indeed, we propose to distinguish analytically two questions which are normally conflated in syntactic analysis. First, we must give some interpretation to the dictum that configurational analysis treats a system from 'all of its elements'. We want to specify the midpoint of *road segments* as the units of analysis—that is, as the basic spatial elements whose configuration defines a given urban area. It is true that our data are already formatted in a discrete form as a set of line segments, but our choice of road segment, rather than the line segment, as the unit of analysis recognizes that the line segment is largely an arbitrary entity—an artifact of the method by which the map is digitized—whereas the road segment is an accurate representation of the topology of the given street network. Furthermore, this allows us to define our spatial elements as being separated by nodes that are actual decision points.

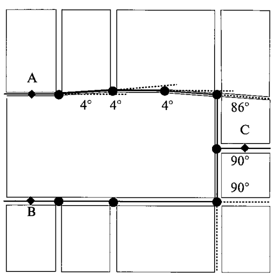
Second, we must give an interpretation of what counts as a direction change. In traditional line analysis a direction change is equivalent to the transition from one line to another. This has given rise to at least two criticisms. Ratti (2004) has pointed out that very small changes in urban layout, affecting, for example, the width of streets or the rotation angle of one urban block with respect to another, may determine the

number of lines that are needed to cross an area. In other words, very small quantitative changes in one variable bring about rather significant changes in syntactic structure. Furthermore, once the lines have been decided, the traditional line map does not distinguish between changes of great angular magnitude, such as right angle turns, and changes of a very small magnitude, even though such differences have been treated as significant (Hillier, 1999b). One response to this problem has been the analysis of angular distances as well as directional distances, whereby angular increments of direction change are added up instead of counting the number of direction changes (Dalton, 2003; Hillier and Iida, 2005). It must be noted, however, that adding up angular changes while still dealing with traditional line maps poses a problem of directional interpretation at each node, as the same intersection will represent different angular changes depending on the direction from which one enters the intersection and the direction in which one leaves. Dalton (2003) has offered an ingenious solution to this problem by using imaginary numbers to store directionality on top of the traditional representation of the line map.

Here we argue that direction change should be handled in a third way. From traditional space syntax we adopt the premise that spatial cognition and spatial function are essentially driven by a topological interpretation of network relationships on a large scale. This implies that we should deal with direction changes rather than with angular measures of the amount of a direction change. At the same time we are very aware of the arguments presented by Ratti (2004) regarding the seemingly arbitrary sensitivity of syntax to very small geometrical differences; this implies a need to control the relationship between geometric and topological properties. We are even more aware of the prior arguments presented by Hillier (1999a) regarding the fundamental importance of the wide angle of incidence often sustained by the long and most accessible lines, implying small direction changes as we move from one to the next; if distinct lines meeting at wide angles function as if they were quasicontinuous then we should have a form of analysis that incorporates such potential forms of quasicontinuity in its premises. In addition, studies in spatial cognition alert us to the fact that people do not keep track of angular changes in their direction of movement continuously, but rather with reference to two egocentric axes—a primary one along their line of sight and a secondary one at right angles to it. A number of researchers (Montello, 1991; Sadalla and Montello, 1989) have reported that errors made by subjects given tasks of orienting themselves in space are systematically biased towards these axes.

In the light of all these observations, we propose to treat direction changes as binary states—either a change in the line of movement registers as a direction change, or it does not. But unlike the traditional line map, in which any change in the line of movement, however minuscule, would register as a turn, we propose to use a threshold value for the angle over which a turn would be registered. The procedure for computing directional distances between two locations in an urban area would be as follows: begin with the *line* segment on which the start location is situated, and find the shortest chain of line segments connecting it with the segment on which the end location is situated. Then cumulatively count every transition to the next line segment in the chain as a unit addition to the directional distance, but only if the angular deviation in moving from one line segment to another is larger than the threshold value.

This definition of directional distance is graphically illustrated in figure 7 and contrasted with the traditional definition of syntactic directional distance as well as the standard definition of angular distance. We note that our definition of directional distance is intellectually in tune with the idea of 'continuity lines'—that is, aggregation of consecutive axial lines respecting a maximum degree of sinuosity—originally proposed by Figueiredo and Amorim (2005). Their work constitutes an important



	From A to C	From B to C
Syntactic distance (in steps)	5	2
Angular distance (in degrees)	188	180
Directional distance—for a 5° threshold angle (in steps)	2	2

Figure 7. Direction distance compared with syntactic and angular distance.

innovation in space syntax and has influenced ours. Here, however, we completely dispense with the axial line as a primary element in the calculation of directional distances and in the description of street networks, as will be further discussed below.

For computing directional distances for an entire area, this procedure would be extended as follows: begin with the middle point of each *road* segment. Use the line segment on which this point is situated to establish the original line of movement. Move out towards both the ends of this line segment, and, following all branches, begin cumulatively adding the direction changes if the angle of deviation is larger than the threshold value. Stop if all the segments have been visited, or if a specified metric distance threshold is reached, or a specified number of direction turns has been exhausted, depending on the specifications of the calculation (see below for formal definitions).

Our definition of directional distance has three implications. The first concerns the interaction between elements and relationships. In traditional syntactic analysis it is assumed that the elementary directional elements are fixed, given a set of conventions and parameters for the analysis of a system; by contrast, in our analysis directional elements are artifacts of the procedure of counting. As such, they are dependent upon the position from which the analysis starts. In other words, they are continuously redefined as we change the starting point. This can be summarized by considering an elementary Y-system which, for sufficiently small angles of direction change, can appear as a single directional element when interpreted from its trunk, and as two directional elements when interpreted from its branches. This is shown in figure 8. The example clarifies that the foundations of our analysis imply no commitment to the perceptual or

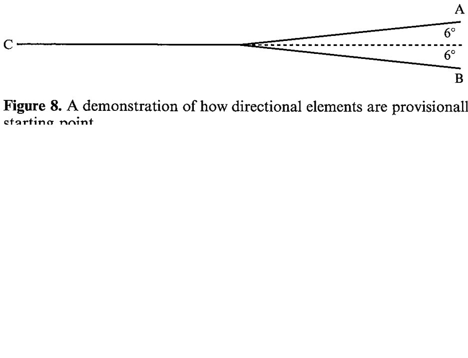


Figure 8. A demonstration of how directional elements are provisionally defined according to the starting point.

cognitive ontological status of directional elements. This responds to Steadman's (2004) objection. By extension, one of the underlying questions of a theory of human space is more explicitly recognized: What is the interplay between perceptual and higher-order cognitive units of relational understanding? Or, put another way, how should we study the integration of simpler units, such as the road segment, into more complex ones?

The second implication is methodological. The extent of directional elements can be arbitrarily but controllably sensitive to the parameters of the analysis, specifically the threshold angle. This meets Ratti's (2004) objection regarding the relationship between the topological representations of syntax and geometry, at least insofar as it explicitly brings the issue of sensitivity into control.

The third implication is perhaps obvious. A center-line approximation to the traditional axial line arises when the threshold angle is set to 0 degrees. In principle, in other words, the syntactic definition of directional distance—not the syntactic definition of the axial line—becomes a limiting case of our analysis. Similarly, if the threshold angle is set to 360 degrees, the entire street network appears as a single element from all points, and all that remains to be discussed is the number of loops involved—that is, the basic topology.

Noise in the data and the definition of the very short line segment

GIS data include certain kinds of 'noise', which must be overcome in order to be able to implement any analysis based on the concepts presented in this paper. While our aim here is not technical, there is one kind of noise that we have to acknowledge explicitly because our response to it becomes embedded in the parameters of the analysis of directional distances. The line segments used in order to represent roads can be arbitrarily small. In different areas of the same city different assumptions are made as to how short these lines should be in order to best approximate curvilinear streets. In principle, if very short lines are used, even a relatively sharp direction change can resolve itself into a great number of smaller direction changes that might pass the test of a reasonably small threshold angle. To control this possibility we check the length of each line segment against a metric threshold. When the analysis encounters two or more consecutive 'very short line segments'—that is, segments below the threshold—it starts adding up the angle of direction change. While the aggregate angle remains below the threshold value no direction change is detected. As soon as the threshold is crossed a direction change is registered and a new angle addition is initiated following a similar process, until the sequence of line segments is exhausted. In this manner direction changes above a threshold (which might otherwise remain disguised due to the use of very short line segments) are detected. Thus, the analysis of directional distances from points involves two metric parameters, the basic parameter of the angle threshold and the secondary parameter of what counts as a very short line segment. The second parameter is expressed as a proportion of the length of the average road segment in the system. The length of the average road segment is an objective property which does not depend on the length of the constituent line segments.

Directional reach

We define the *directional reach* $R_u(P_i, \delta, \alpha, r)$ of a point P_i according to a directional threshold δ as the aggregate length of the road segments and fractions of road segments that are no more than δ direction changes away, subject to a direction change threshold angle α and a very small line segment threshold set to a fraction r of the average road segment length. When δ is set to 0, $R_u(P_i, 0, \alpha, r)$ expresses the length of the directional element which comprises P_i. When δ is set to 2, $R_u(P_i, 2, \alpha, r)$ expresses the total length of streets that are up to 2 direction changes away from a given point. The variation of this quantity along a street, and specifically its local increase, is directly associated with the idea of the local intensification of a grid, studied by Hillier (1999a).

Directional-metric reach

We define the *directional-metric reach* $R_w(P_i, \delta, \mu, \alpha, r)$ of a point P_i according to a directional threshold δ and a metric threshold μ as the length of all road segments and fractions of road segments which are no more than μ metric distance, and no more than δ directional distance, away from P_i, subject to a threshold angle α and a ratio r for defining very small line segments.

Sets of road segments associated with reach measures

The three measures of reach, $R_v(P_i, \mu)$, $R_u(P_i, \delta, \alpha\ r)$, and $R_w(P_i, \delta, \mu, \alpha, r)$, are associated with metric units. They are measures of length. However, each of these measures is associated with a set of road segments and fractions of road segments. We will refer to the corresponding sets as $S_v(P_i, \mu)$, $S_u(P_i, \delta, \alpha, r)$, and $S_w(P_i, \delta, \mu, \alpha, r)$ respectively.

The difference between the $S_v(P_i, \mu)$ of a point P_i and the $S_w(P_i, \delta, \mu, \alpha, r)$ of the same point captures the areas that are less likely to be visited from P_i, even though they are metrically as accessible as others, owing to the greater number of direction changes involved. Thus, by setting different values for μ and δ, we can study whether movement from a point is likely to be drawn to some parts of its accessible surroundings more than to others, according to directional distances, while taking metric range into account at the same time.

Directional distances with respect to reach

The next step in our analysis is to propose a more precise measure of the directional distance that characterizes the relationship of a point to its surroundings. For this purpose we take any of the three types of reach for granted and ask what is the average directional distance of all points included in the associated set of the reach from the point taken as origin.

We define the total length of road segments and fractions of road segments that are exactly d directional changes away from a point P_i subject to a threshold angle α and a very small line ratio r as $L(d, \alpha, r)$. Clearly, the overall street length that lies on the reach of a point will be distributed into components $L(1, \alpha, r)$, $L(2, \alpha, r), \ldots, L(n, \alpha, r)$, according to whether the directional distance of the line segments involved is $1, 2, 3, \ldots, n$. Also, by definition, if we allow d to vary as necessary, the sum $L(1, \alpha, r) + L(2, \alpha, r) + L(3, \alpha, r) + \ldots + L(n, \alpha, r)$ will be equal to the reach involved. Thus, we arrive at the following formal definitions.

$$D_v(P_i, \mu) = \frac{\sum_{d=0}^{n} \mathrm{d}L(d, \alpha, r)}{R_v(P_i, \mu)}\ , \tag{1}$$

where $D_v(P_i, \mu)$ is the directional distance of a point P_i with respect to a set $S_v(P_i\ \mu)$, $L(d, \alpha, r)$ is the total L of all road segments and fractions of road segments which lie d direction changes away, $R_v(P_i, \mu)$ is the metric reach of a point P_i with metric threshold μ, and n is the maximum directional distance from P_i to any member of $S_v(P_i, \mu)$.

$$D_u(P_i, \delta, \alpha, r) = \frac{\sum_{d=0}^{\delta} \mathrm{d}L(d, \alpha, r)}{R_u(P_i, \delta, \alpha, r)}\ , \tag{2}$$

where $D_u(P_i, \delta, \alpha, r)$ is the directional distance of a point P_i with respect to a set $S_u(P_i, \delta, \alpha, r)$, $L(d, \alpha, r)$ is the total L of all road segments and fractions of road segments which lie d direction changes away, $R_u(P_i, \delta, \alpha, r)$ is the metric reach of a point P_i with directional distance threshold δ, angle threshold α and a very small line ratio r, and δ is, by definition, the maximum directional distance from P_i to any member of $S_u(P_i, \delta, \alpha, r)$.

$$D_w(P_i, \mu, \delta, \alpha, r) = \frac{\sum_{d=0}^{\delta} \mathrm{d}L(d, \alpha, r)}{R_w(P_i, \mu, \delta, \alpha, r)}\ , \tag{3}$$

where $D_w(P_i, \mu, \delta, \alpha, r)$ is the directional distance of a point P_i with respect to a set $S_w(P_i, \mu, \delta, \alpha, r)$, $L(d, \alpha, r)$ is the total L of all road segments and fractions of road segments which lie d direction changes away, $R_w(P_i, \mu, \delta, \alpha, r)$ is the metric reach of a point P_i with metric threshold μ, directional distance threshold δ, angle threshold α and very small line ratio r, and δ is, by definition, the maximum directional distance from P_i to any member of $S_w(P_i, \mu, \delta, \alpha, r)$.

Here we propose no normalization of relativization of directional distance values. Normalization on purely mathematical grounds is not possible: the minimum directional distance of a system is still 0, because theoretically the whole system could be a single line of the necessary length; however, in order to determine the maximum theoretical directional distance, we would have to make an assumption about the minimum metric interval that would correspond to a single direction, before being able to compute the theoretically highest number of direction changes afforded to any given line length. Thus, the problem of mathematical normalization intersects the problem of empirical relativization, the adjustment of values taking into account empirical comparative data. In 'lines' or 'axial' analysis this issue does not arise, because the number of elements in the system is taken as a given and, therefore, the maximum theoretical directional distance is a unilinear sequence with that number of elements; here the number of directional elements is not given. We defer the question of relativization until a sufficient number of cases have been analyzed, so as to support the development of an explicit theory for the comparative analysis of cities that may include the need for relativization functions. At this stage the simple values associated with reach and directional distance have the advantage of making direct intuitive sense, in addition to being mathematically well defined. Taken together they can characterize with considerable power the relational position of a road segment within a network of streets, as we will see in the next sections.

Directional distance with respect to reach for street networks

Street networks and parts of street networks can be characterized by the average directional distance values associated with the midpoint of all road segments in them: $\bar{D}_v(P_i, \mu)$, $\bar{D}_u(P_i, \delta, \alpha, r)$, $\bar{D}_w(P_i, \mu, \delta, \alpha, r)$, respectively, with i ranging between 1 and k, where k is the number of road segments in the system under consideration.

The third column of table 1 provides $\bar{D}_v(P_i, 1\ \text{mile})$ values for the sample of twenty-five 2 mile × 2 mile areas of Atlanta that have been previously discussed. It will be seen that the older cities (Atlanta, Marietta, Decatur, College Park) and early suburbs (Ansley Park, Virginia Highland) have smaller directional distances than the emerging commercial and business centers (Dunwoody-Perimeter Mall) and the outlying areas (Crabapple, Peachtree City). New urban centers with unevenly distributed densities of development (Buckhead) appear to evolve on the basis of street networks approximating the directional breakup of early suburbs. By and large, there is a tendency for directional distance to increase as metric reach falls ($R^2 = 0.61$, $p = 0.0001$).

This finding indicates that, as urban blocks become larger (thus producing smaller metric reach values), so the street network becomes more curvilinear and fragmented (thus producing higher directional distance values). This tendency is characteristic of Atlanta urbanism (and perhaps more generic to postwar trend in US urbanism), and is not a mathematical necessity. Of course, this is hardly a surprising finding to anyone that studies US cities. It would appear, however, that metric reach and directional distance values, as defined here, capture and quantify some of the fundamental morphological properties of the evolving fabric of roads in metropolitan Atlanta in a way which helps us to benchmark any given area against the range of variation that prevails in the region at large.

Treating the twenty-five areas as independent systems, we also sought to determine whether directional distance increases as a function of the variables which describe the aggregate metric properties of the system: number of blocks per square mile, number of intersections per square mile, and street length per square mile. The correlations between these variables and directional distance were all significant, negative, but not very strong ($R^2 = 0.49$, $p = 0.0001$; $R^2 = 0.44$, $p = 0.0003$; and $R^2 = 0.42$, $p = 0.0004$, respectively). Two other variables turned out to be more strongly and positively associated with directional distance: the number of intersections per block ($R^2 = 0.60$, $p = 0.0001$), and the street length per block ($R^2 = 0.57$, $p = 0.0001$). We infer that directional distances increase as a consequence of two factors, a greater number of T-junctions as compared with street intersections, and larger blocks surrounded by curvilinear streets. Once again, when we take averages in order to characterize urban areas, our measures are correlated with simpler measures similar to those used in existing literature. However, our measures retain the important advantage that they can also be used to characterize individual road segments and discriminate in describing conditions inside urban areas. Put simply, our measures, like all previous syntactic measures, lend themselves to understanding the interaction between local and global properties, the relational properties of individual spaces and the relational properties of systems.

A pilot study of movement

One of the members of our research team, Ayse Ozbil, has taken pedestrian and vehicular counts at thirty-eight gates in the Virginia Highland neighborhood of Atlanta. The neighborhood was developed as a streetcar community in the early 20th century. Its focus is the intersection of Virginia and North Highland Avenues. Today it is one of the most pedestrian friendly urban neighborhoods near the center of Atlanta, mostly comprised of residential areas but also including a number of restaurants, bars, and retail establishments, particularly along North Highland. The count at each gate was taken over a total of twenty minutes, during working hours over one week in April 2006, and was intended only as a preliminary snapshot of the area.

The mean number of pedestrians per twenty minutes was slightly over 25; the maximum density was 118 and the minimum was 0. The mean number of cars was 119 per twenty minutes; the maximum was 400 and the minimum was 4. The gate counts were correlated with standard space syntax measures and with the measures proposed in this paper. For the purpose of standard syntactic analysis, an axial map was drawn manually over a larger area, chosen so as to ensure that every space in the observation area was embedded in such a way as to allow integration radius 3 to be computed without an edge effect. Figure 9 shows the distribution of gates over the syntactic line map and the standard GIS map, with each gate represented as a circle proportional to the density of pedestrian movement.

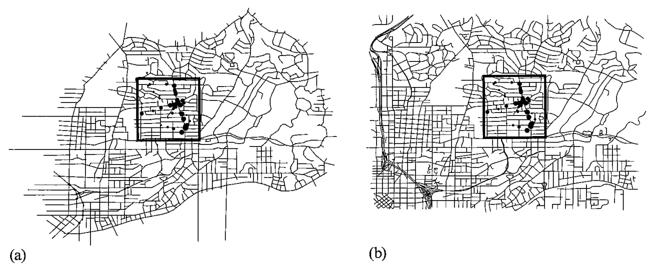


Figure 9. Thirty-eight gates over the Virginia Highland neighborhood in Atlanta: (a) embedded in manually drawn line map of surrounding area, sufficient to allow radius 3 integration to be computed without edge effects; (b) embedded in a section of a GIS map of Metropolitan Atlanta, where all values have been computed without edge effects.

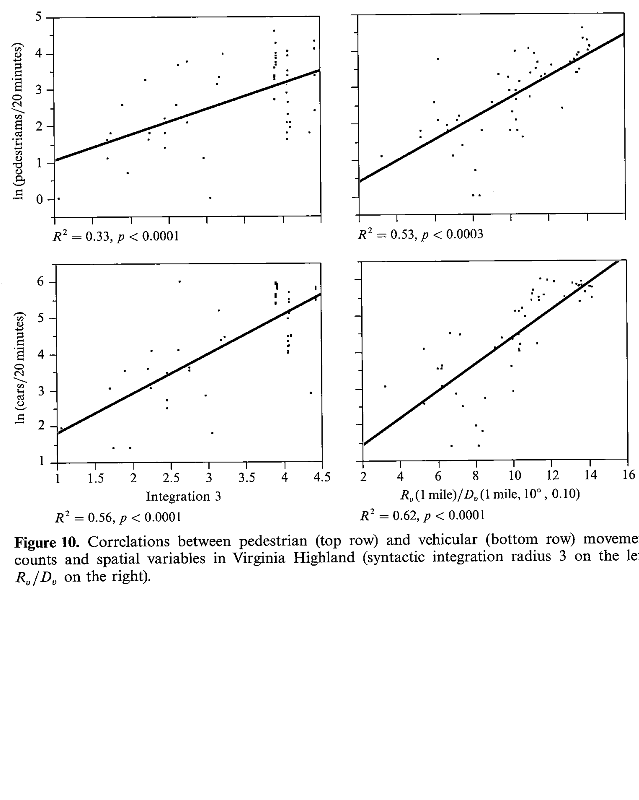


Figure 10. Correlations between pedestrian (top row) and vehicular (bottom row) movement counts and spatial variables in Virginia Highland (syntactic integration radius 3 on the left; R_v/D_v on the right).

We ran correlations between measures of vehicular and pedestrian volumes of movement and integration, integration radius 3, and connectivity, as usually defined in space syntax. The correlation between syntactic variables and movement was best for integration radius 3 against the natural logarithm of movement counts. The correlation between the new variables and movement was best for a composite variable: $[R_v(P_i, 1\ \text{mile})]/[D_v(P_i, 1\ \text{mile}, 10°, 0.10)]$. This variable takes higher values when a space has a large metric reach and a low directional depth, and smaller values when a space has a lower metric reach or a higher directional depth. For cars, the correlations associated with standard space syntax and with the new variables were almost the same. For pedestrians, the correlations associated with the new variables were considerably stronger. This is shown in figure 10.

This very limited pilot study is not intended as a contribution to the theory of natural movement (Hillier et al, 1987; 1993; Peponis et al, 1989). However, it leads us to infer that the new variables are likely to offer good ways to develop and test hypotheses regarding the impact of the configuration of street networks upon movement. The practical implication is that the family of ideas typically associated with space syntax can be brought to bear without having to go through the laborious process of constructing the particular representations of street networks that have been central to space syntax as far as the classical studies mentioned earlier are concerned.

Discussion

In the first part of the paper we discussed connectivity as a generator of urban potential. Urban potential can be thought of as the quantity of destinations that is available within a given distance of movement from a point. Because we are primarily interested in the structure of street networks, rather than land use, we have indexed urban potential by the street length which is available within a distance of movement. Indeed, destinations attach themselves in some way to street frontage. In order to measure the street length that is accessible within a range of distance we have to specify how we measure distance in the first place. We have used metric and directional measures of distance. Thus, we have come to ask the following specific questions and define the corresponding descriptive measures:

(1) How much street length can be reached within a given metric distance? Metric reach: $R_v(P_i, \mu)$. This is essentially a measure of density.

(2) How long can I walk without changing direction? Directional reach for the special case when the threshold of direction changes is set too: $R_u(P_j, \delta = 0, \alpha, r)$. This is a measure of the length of the continuous composite linear elements that make up the urban fabric, subject to specifying an angular threshold for identifying direction changes.

(3) How much street length can be reached within a given directional distance? Directional reach: $R_u(P_j, \delta, \alpha, r)$. This is a measure of syntactic accessibility. It pertains to the insight that, at a local or neighborhood level, directional changes are a significant factor in our judgment of relative distances.

(4) How much street length can be reached within a given metric and directional distance? Directional-metric reach: $R_w(P_j, \delta, \mu, \alpha, r)$. Consistent with the above, this is a measure of syntactic accessibility limited by a metric threshold.

We propose that these questions provide the initial premises for studying street networks as mechanisms that serve the purposes of connectivity in the broad sense. From the point of view of movement, potential access is the fundamental form of spatial relatedness. However, previous syntactic research indicates that movement in urban space is distributed according to relationships of directional distance. There is also evidence in the literature that direction distance is a fundamental determinant of spatial cognition. We have, therefore, proposed measures of directional distance that index how easily accessible potential destinations are. Fundamentally, we have asked what is the directional distance of the average unit length of street that is potentially available as a destination of movement from a given point. Specifically, we have asked the following questions:

(5) What is the directional distance of the average destination that I can reach within a given metric distance? $D_v(P_i, \mu)$.

(6) What is the directional distance of the average destination that I can reach within a given directional distance? $D_u(P_j, \delta, \alpha, r)$.

(7) What is the directional distance of the average destination I can reach within a given directional and metric distance? $D_w(P_j, \delta, \mu, \alpha, r)$.

Our measures of directional distance facilitate the study of the connectivity of street networks represented according to standard GIS conventions. However, our measures are defined in a way which also avoids some of the criticisms that have been raised regarding established methods of syntactic analysis. Specifically, we make no prior assumption about the existence of directional elements, or their perceptual or cognitive status. Also, we define direction changes parametrically, so that analysis can be arbitrarily sensitive. In this manner we provide a methodology which does not preempt the conclusions that will arise from the empirical study of substantive questions. For example, do we think of direction changes according to some constant angular threshold, or do we determine what counts as a direction change subject to the underlying geometry of a particular network? What are the relevant thresholds in either case?

This paper contributes to the analytical methodology and the underlying descriptive theory of street networks as configurational patterns. We would, however, like to end with a few pointers to the potential contributions of the proposed framework.

The proposed framework of analysis responds well to recent trends in syntactic studies. For example, how should we understand the relationship between urban centrality and the intensification of the urban grid? Early syntactic studies did not take metric properties into account. Our measures of reach contribute a natural way of measuring how a grid becomes metrically denser or sparser, while our measures of directional distance provide a natural way of measuring how a grid becomes more intelligible and easily accessible. Thus, we set the stage for studying how the properties of the grid might relate to land use and the intensity of development.

Our pilot field study indicates that our measures are likely to capture at least as well as standard syntactic measures the manner in which movement is distributed according to the configuration of the street network. Because they take the road segment as the unit of analysis, they are likely to respond well to the increasing interest, in syntactic studies, of how densities of movement may vary along a single linear street, depending on the local relationship between street segments and the surrounding network. Just as important, the parametric control over what counts as a direction change and the explicit control over the metric range of the analysis has advantages regarding future studies of how urban movement relates to spatial cognition.

Finally, our approach might help to bridge the gap between understanding urban structure, urban design, and urban regulation. This possibility arises in part from the ability to control the interaction between metric and nonmetric variables. More important, it arises from the ability to ask explicit questions about the interaction between urban parameters, such as blocks per square mile, street length per square mile, the distance between street intersections, or the number of intersections per square mile and the morphological structure of connectivity. The better we understand these interactions, the higher the chances that we might be able to influence the emergent structural properties of connectivity of street networks by controlling some of the parameters of urban design and layout.

Acknowledgements. The first author thanks Evita Periklaki for advice regarding the mathematics of the argument presented in this paper and Bill Hillier for correcting errors in an earlier draft.

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