377

Route Choice from Local Information

Comparing Theories of Movement and Intelligibility

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ABSTRACT

Intelligibility, the extent to which non-local structure can be inferred from local properties, is examined using new methods based on angular segment analysis, demonstrating that such a property is consistent with exosomatic navigation. In many urban networks, effective movement is possible without knowledge of the broader structure, or memory, using information conveyed to a navigator only by the angles of each intersection. Results suggest that this is not due to a particular optimisation of the grid unique to cities, as has been suggested, but can result in a many possible networks, including random ones. A relationship between intelligibility and predictability of movement, implied in previous literature, is shown not always to hold. Additional methodological and theoretical contributions are made in proposing a novel measure of immediate angular intelligibility, and in demonstrating equivalences between this and traditional axial line intelligibility, and between a number of other methods proposed to predict movement in the literature.

KEYWORDS

Intelligibility, Street Segments, Exosomatic, Navigation

1 INTRODUCTION

The various measures of street networks that have been shown to correlate with pedestrian and vehicle movement imply different mechanisms of navigation, with differing amounts of information available to the navigator. Segment angular choice (Hillier and Iida 2005), or betweenness, suggests the selection of optimal, least-angle, routes to a destination based on street geometry, and continuity lines (Figueiredo and Amorim 2005) or natural streets (Ma et al. 2018) suggest a topological map in which the longest units are more attractive; both of these imply a longer-range awareness of the city beyond what is visible at a given point. By contrast, stochastic exosomatic agents (Turner and Penn 2002) and random walks (Fidler and Hanna 2015; Hanna

2021) predict movement based on what is immediately visible from an agent’s current position. The success of the latter methods indicates that individuals can successfully navigate based on local information only, but it is an open question why this should be the case. Is it generally true that such methods correlate with longer range route optimization? Or is this the case for only a small set of possible graphs, of which cities represent a special case in which streets are optimized to convey information about their larger structure to observers locally, maximise intelligibility, and enable navigation?

These are versions of the question of *intelligibility* (Hillier et al. 1987), introduced in space syntax to explain the structure of cities found in the topology of axial line graphs. This paper examines alternative measures of intelligibility in the degree to which long-range structure is evident in the immediate isovist actually visible at individual points. Correlations between measures of random walk distributions, choice (betweenness), and natural streets are compared for a selection of real cities and artificially produced street networks, to determine whether and how this varies with street geometry.

This paper presents evidence of two related types, first looking at the aggregate data equivalent to movement over time (section 3), and then presenting a new measure of *immediate intelligibility* (section 4). In this latter, a measure of edge (rather than node) betweenness in segment graphs is examined to determine the relationship between local angles and the proportion of optimised routes selected at each junction.

2 THEORY

Hillier’s (1999) description of the nature of the deformed grid to explain how space syntax works highlights two theoretical issues still actively debated in the literature. The first is the relationship between geometry and topology as the basic description of urban form. Despite arguing the merits of primarily topological graph representations, detailed analyses of axial networks London and Hamedan presented a case for the relevance of both properties, and suggested that the geometry of cities is such that angle and length of axial lines are related. Most angles between axial lines are either nearly orthogonal or nearly straight; the former are short lines and the latter are long.

The second issue is the relationship between global city structure and individual human choice as generator of movement. Route finding through the network is described as a Markov process: following long lines and then taking the most obtuse angle (close to straight) turns is more likely to lead to other long lines and obtuse angles. This is a statement of an assumption of angular minimisation later implied in angular segment analysis (Hillier and Iida 2005) continuity lines (Figueiredo and Amorim 2005) and natural streets (Jiang et al 2008) and found in empirical observation (Turner 2009). But what it suggests is both that there is an important relationship between local and global structure, and that it is through a process of movement that local properties may pick up non-local properties.

The following two sub-sections, 2.1 and 2.2, review these topics individually before setting out the line of empirical investigation in section 2.3.

2.1 Competing representations: geometry versus topology

In representing spatial networks for analysis, space syntax methods have differed in using either topology or geometry. Topological approaches have measured the properties of a graph formed from theoretically fundamental units such as axial lines (Hillier 1999, Penn 2003) based on static lines of sight, or continuity lines (Figueiredo and Amorim 2005) and natural streets (Jiang et al 2008) based on movement. Geometrical approaches, often still graph-based, have incorporated geometrical measures of distance or angle, as in angular segment analysis (Hillier and Iida 2005) or visibility graph analysis (Turner et al 2001). Approaches approximating actual movement in the form of random walks have similarly been divided between those using topology, either walking directly on graphs (Blanchard and Volchenkov 2009) or topologically weighted (Jiang and Jia 2011), and those using geometry, either in visual simulation (Turner and Penn 2002) or in weighted graphs (Hanna 2021).

Claims have been made that one or the other approach is fundamental. Topological line graphs have been said to capture the “true geometry of cities” (Hillier 1999), and it has even been asserted that geometrical representations are incapable of capturing relevant properties of structure and human behaviour, and correlate poorly with such observations (Ma et al 2018). Conversely, ample evidence has been given for geometrical properties such as turn angle as directly linked to observed movement (Turner 2009) and these have been shown to have good predictive capacity (Turner and Penn 2002; Hanna 2021). No consensus yet exists as to whether any single measure is clearly superior.

Instead it might well be that both measure the same phenomena with different methods. Hillier (1999) argues that the topological (axial) “line graph analysis doesn’t ignore the geometric properties of space but internalises them into the graph”. Angular segment analysis (Hillier and Iida 2005), a geometrical method developed subsequently, captures these internal geometric properties directly by summing the total angular cost of routes: traversing many segments with no angular change has a total angle of zero, which is identical in overall route cost to the axial line. The topological analyses of continuity lines and natural streets similarly form units based on geometry, and so the same rough equivalence holds. In this light the above question as to which method is superior may instead be cast as an empirical question of just how well one method represents the information of the other.

What is different between topological and geometrical representations is the scale of resolution, as the basic units of topological methods tend to be coarser. Axial lines and natural streets are composed of many individual segments; Hillier (1999) notes "the line is the least local representation of space" because it aggregates geometry across a large distance. To the extent this resolution is a problem, and to the extent the topological and geometrical approaches are revealing the same underlying phenomena, instead of measuring the topological properties we may gain a more detailed understanding by measuring the geometrical properties directly. Intelligibility, for example, has been studied previously using measures of topology (axial lines); but geometry may also be important.

2.2 Intelligibility: local and global

Intelligibility is the extent to which "the whole can be read from the parts" (Hillier et al 1987). It is a second order measure of the correlation between a local and a non-local network property, originally the connectivity of an axial line and integration, and describes the degree to which one can infer the global structure of the network from what is visible from a single location. It has been shown empirically to be strongly related to an area's predictability of movement: poorly intelligible areas show less predictability of movement than highly intelligible (Hillier et al 1987; Chang and Penn 1998; Hillier 1996; Penn 2003; Zhang et al 2013).

Intelligibility thereby raises questions as to how individuals are actually able to navigate. Because the space syntax measures that correlate best with observed movement are allocentric (network centrality), not egocentric (Penn 2003) they do not directly explain how this information gets inside the head of a navigator. One hypothesis is that we estimate an analogue to these measures from an internal mental model of the space. Segment angular choice, which assesses the proportion of minimal-angled paths throughout the network that pass through a given segment, successfully indicates the expected level of through movement (Hillier and Iida 2005), and requires a full knowledge of the whole network to optimize and sum routes. Integration is also non-local; it has been claimed that it is more easily intuitable (Hillier et al 1987), but only by building up knowledge of the network through movement over time, and is also a model, albeit of a different kind. Proposals that link such measures directly to navigation imply that we are route optimisers operating with an internal mental representation.

Opposed to this is the exosomatic hypothesis, that this information is not in the head but directly visible in the space (Turner and Penn 2002). Penn (2003) suggests that human cognition is a "correlation detector" using locally observable properties to infer the long-range structure relevant to route choice decisions, and as such this hypothesis is directly dependent on intelligibility. Figure 1 shows *intelligibility* as the relationship between local and global network properties, and *predictability* as the relationship between global properties and movement. In a well-functioning network, where both correlations are high, we should expect a similarly strong correlation in the remaining side of the triangle, between local properties and movement. This is the principle behind exosomatic visual agents (EVAS) in which a memoryless agent makes route choices based on its immediate view (Turner and Penn 2002), and on certain other implementations of random walks (Hanna 2021), all of which base movement directly on local properties. The intelligibility assumptions behind exosomatic navigation are supported by the empirical success of such models, and by evidence that both individual navigation choices, and actual post-hoc representations in the form of sketch maps have been shown to improve or degrade with intelligibility (Penn 2003).

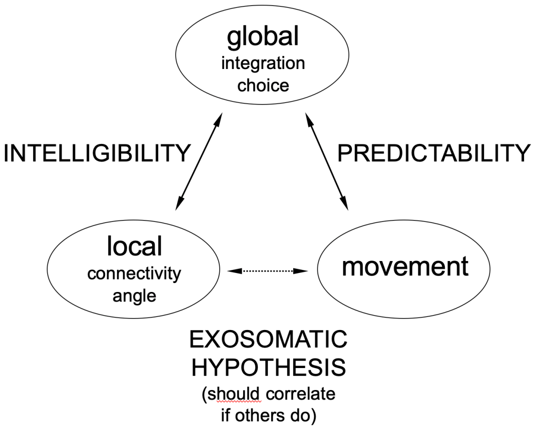

Figure 1: Intelligibility and predictability as correlations between local, non-local and movement.

Intelligibility, as a correlation, is an aggregate measure that can only be defined over a significant number of samples (a neighbourhood or a city), but the definition of local and non-local properties can be at different levels of scale. Rather than global integration it may be limited to a scale known to correspond better to movement like radius 3 (Penn 2003), or the same local integration used as the local variable instead of connectivity (Hillier 1996). The connectivity of the axial line is assumed to be the most local, but even this may not actually be visible from a particular point in a street, especially if it is long. This presents a problem in accounting for the actual mechanisms of perception where intelligibility is linked to navigation.

Much space syntax research has increasingly adopted segment-based representations since (Hillier and Iida 2005) as an alternative to axial lines, partly due to their availability in multiple formats of publicly available road centreline maps, and partly due to increased resolution. Axial lines may be formed of multiple segments, but aggregate these properties across the whole line. The same is true of continuity lines (Figueiredo and Amorim 2005) and natural streets (Jiang et al 2008) which are composed directly from aggregation of segments which do not exceed a particular angle of turn. Segment representations, if measured directly, can yield different properties between every road junction.

Unfortunately, classic intelligibility makes little sense for segments due to a lack of variance in connectivity, as segments connect only at each end. Thus, as central as intelligibility is to space syntax theory, it has not been fully incorporated into the work above. Following methods of angular analysis (Hillier and Iida 2005; Turner 2009; Hanna 2021) the comparative analyses in sections 3 and 4 instead use segment angle as the local property, and introduce a new method for doing so. Several analytical methods are used in section 3, each of which varies in the scale of information required by an implicit navigator: angular weighted random walks (Hanna 2021) are the most local, natural streets (Jiang et al 2008) aggregate across whole roads, and angular choice (Hillier and Iida 2005) is a global centrality measure. Section 4 uses segment angle directly as the local variable of intelligibility. In contrast to axial connectivity, this angle is directly visible from a single point in the grid, and may be the most local property that can be measured.

2.3 Are cities unusual?

Intelligibility may be thought of as the comparative effectiveness of the street network in conveying information to an individual. As such is a theoretically desirable quality suggesting why one neighbourhood works well compared to another (Hillier et al. 1992; Hillier 1996), and observations of poorly functioning neighbourhoods with low intelligibility support that its lack contributes to their poor function. Hillier (1996, p. 131) describes the case as one in which "interfaces are broken".

Just how cities achieve high intelligibility and predictability, and how likely these are, are also open questions. Hillier (1999) proposed a geometrical description which remains an intuitive picture of the intelligible deformed grid by relating angular with metric properties: longer lines meet at obtuse angles and short lines meet at near-orthogonal angles. This intuitively describes the movement resulting from various models of geometry-based random walks (Turner and Penn 2002; Hanna 2021). Hillier asserts this is near-invariant in cities, but unlikely to have evolved by chance, and that some kind of "consistent constructive process at work" (Hillier 1999). Hanna (2021) suggests that the correlations found between local, global and movement may be because some cities and networks are particularly well optimised for information carrying. Intelligibility doesn't exist in pure grids, for example, nor does Hillier's geometrical relationship: all lines are long and all are perpendicular. Any slight change introduced by a bend in a long line makes this even worse: the two shorter axial lines become the only ones with obtuse angles. Sections 3 and 4 will attempt to answer whether the intelligibility/predictability relationship is necessarily true, true in many cases, or a rare occurrence that is an optimised property of cities.

Figure 1 also suggests that, while related, to assume predictability (of movement) is a function of intelligibility (or vice versa) is potentially to conflate distinct attributes. In cases where correlations are high between the two we would expect to see movement corresponding to exosomatic navigation, but this also suggests testing cases in which intelligibility or predictability is low. London, New York and several constructed street networks sit at various points within this triangle of relationships, and will be used in an attempt to shed light on them.

3 CORRESPONDING MEASURES: EVIDENCE FROM DISTRIBUTIONS

As noted in section 2.1/2.2, sources disagree as to whether movement is primarily a function of geometry (Hillier and Iida 2005) versus topology (Hillier 1999; Ma et al 2018), and our navigation memoryless and exosomatic versus following planned routes (Turner and Penn 2002; Hillier and Iida 2005, Hanna 2021). Evidence for each assertion has been based on correlations of aggregate movement with measures of space; the same approach is taken here, initially, to test whether one measure really is better than another at predicting movement.

The three main measures also rely on different degrees of local/global information. A simulated random walk (Hanna 2021) is the most local, based on the immediate angular weighting between adjoining segments at a single junction. Natural street degree (Jiang et al 2008) is longer range, as the basic units of natural streets are formed in advance by a comparison of angles along their length, and the joining of segments with turns less than a given threshold angle. Angular segment choice (Hillier and Iida 2005) is the most global measure, as it relies on the comparison of full paths through the network. The different levels of local information allow an investigation into alternative versions of intelligibility by comparing correlations between the more local and more global measures.

3.1 London

A comparison is shown below between segment angular choice, natural streets, and a weighted random walk as predictors of movement. All analyses were performed on a map of London within the M25, taken from the Ordnance Survey (OS) Integrated Transport Network layer of July 2011. Segments represent road centrelines between junctions. The map covers approximately 61km by 55 km, and consists of a total of 312,037 segments, with a mean length of 74.2 m. Two sets of traffic data are used. The first is that used in numerous previous studies of movement and intelligibility (Hanna 2021; Hillier and Iida 2005; Jiang 2009; Penn et al. 1998), consisting of 234 vehicle traffic and 319 pedestrian counts clustered locally and densely in selected neighbourhoods of Barnsbury, Clerkenwell and Kensington-Knightsbridge. The second consists of traffic data taken from the annual average daily flows of vehicles recorded in 2018 and publicly available from the UK Department for Transport. This set is of a broader area and range of street types; samples identified within 10m of a London map segment centre line were used, resulting in 290 data points.

Figure 2 compares the several measures, expressed as a rank (Spearman) correlation with observed vehicle traffic in London. For each measure, a reasonable approximation is used of its most favourable parameters according to the literature. Angular choice is measured at a radius of 4000 m, known to be a good predictor of movement (Hanna 2001). Natural streets were defined by consecutive segments joining with a maximum threshold of 30 degrees, and measures are used of both the number of segments in the street and of its connectivity (degree), or number of connecting streets; the latter previously shown effective in the literature (Jiang et al 2008; Jiang and Jia 2011; Ma et al 2018). Each of these static measures is indicated by a horizontal line, whereas an angular weighted random walk is shown varying over 100 iterations, indicating a period of convergence over the first 20-30 iterations and relative stability thereafter. Random walks are calculated with a weighting based on segment angle raised to the power of 4 or 5, as in (Hanna 2021). The left plot indicates traffic within the local neighbourhood data set; the right for the larger UK DfT set. Table 1 also summarises these correlations numerically for the same data, and for the data set of pedestrians within the same local neighbourhoods.

It is evident in both the plots and table that there is little difference between each measure in approximating observed movement. Correlations are consistently high for both sets of vehicle traffic data, with overall means approaching $\rho \approx 0.8$ and little difference between measures ($\sigma = 0.015$ for neighbourhood samples and $\sigma = 0.024$ for all London). Correlations are not particularly high for the pedestrian traffic (this may be the result of the OS centreline graph used here, as higher correlations to the same data have been reported in the literature using axial line derived graphs, e.g. $r \approx 0.75$ in Hillier and Iida 2005; $r \approx 0.82$ in Hanna 2019), but are consistently in the range of $\rho \approx 0.6$ to $\rho \approx 0.67$. Averaging all correlations in Table 1 across data sets, all random walks yield a mean correlation of $\rho = 0.72$ ($\rho = 0.78$ for vehicles), all natural streets yield $\rho = 0.73$ ($\rho = 0.77$ for vehicles) and angular choice yields a mean correlation of $\rho = 0.76$ ($\rho = 0.81$ for vehicles). The similarity between these values does suggests that no single type of measure stands out as a better predictor of movement than the others. In the case of London, at least, each type of measure provides good, roughly equally good, estimates of movement.

If these measures represent different hypotheses about navigation (exosomatic vs. planned) there is nothing to suggest one over the other within the London data. All are consistently high; navigators could be relying on immediate exosomatic information but just happen to correlate with planned optimal routes (or vice versa) because of the structure of London itself. If this is the case, it would be in line with the hypothesis relating intelligibility and predictability, but only in one causal direction: local to global intelligibility produces a good prediction of movement, not necessarily the other way around.

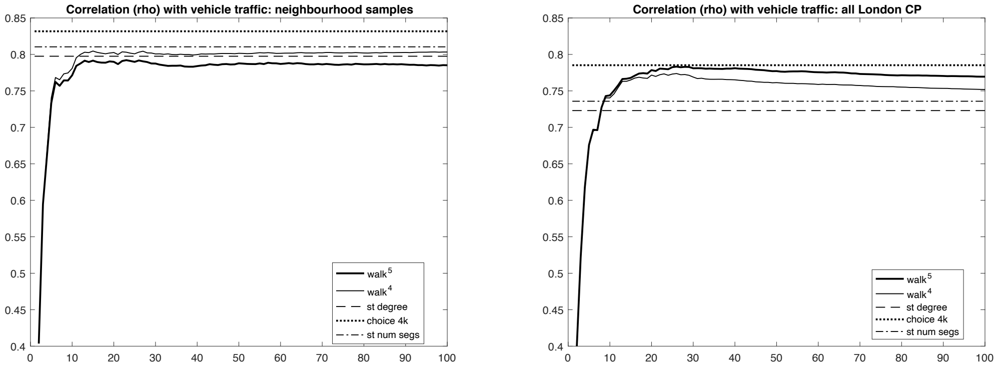

Figure 2: All measures are well correlated with London vehicular traffic: samples from local neighbourhoods (left) and London-wide survey (right). [Natural streets defined by 30 degree threshold.]

Table 2: London correlations (Spearman) with pedestrian and vehicle traffic

	Walk^4 26 it. (& 100 iter)	Walk^5 26 it. (& 100 iter)	NatSt Degree (& num Segs)	Choice rad 4km
pedestrians: 319 neighbourhood samples	0.61 (0.61)	0.60 (0.60)	0.65 (0.65)	0.67
vehicles: 234 neighbourhood samples	0.80 (0.80)	0.79 (0.79)	0.80 (0.81)	0.83
vehicles: 290 all London samples	0.77 (0.75)	0.78 (0.77)	0.72 (0.74)	0.79

3.2 New York

What about the other direction: does predictability also imply intelligibility? New York has a very different structure consisting of far more streets arranged in regular grids, a pattern itself known to be problematic for traditional intelligibility measures due to the lack of variation between axial lines (Zhang et al 2013). As such, it might be expected to have poor intelligibility and poor predictability of movement (Hillier et al 1987; Penn 2003; Zhang et al 2013).

Analyses were performed on a map of New York, edition 19D of the LION file issued by the NYC Department of City Planning's Geosupport System. Of a total count of 228,011 objects, 163,246 segments representing vehicular road traffic were used, covering an area of approximately 45 km by 45 km. Traffic data were taken from counts over the period 13 September 2014 to 15 April 2018 published by the NYC Department of Transportation. This set provides hourly counts for each day, by direction of travel, surveyed from 1388 distinct locations over 372 streets, although different subsets are not consistent across survey days. The data set of 514,752 total count values was prepared by taking the value of all daily traffic at each survey point averaged over all days included in the survey, resulting in 1388 values for vehicle traffic.

Table 2 shows correlations between traffic and measures comparable to those in section 3.1, and several additional versions of the same. Random walks based on more extreme weightings were seen to have slightly better correlation with New York traffic, and so angle raised to the power of 10 is shown, in addition to the power of 5 used in previously published studies of London (Hanna 2021). Natural streets of a higher threshold of 75 degrees are included alongside the previous 30 degrees. The imperial equivalent of 4000 m used above for angular choice radius is approximately 13,123 ft; values for radii bound this at 10,000 ft and 20,000 ft, and include radius n (the full graph). The log/log Pearson correlations values for each are also shown in addition to the rank correlations used above. In no cases is a measure found to be particularly successful at approximating traffic counts. Both the more extreme random walk and natural streets give the best correlations, just exceeding 0.4 for both rank and log/log, but no measure exceeds a value of 0.46, and most are considerably lower. Unlike London, the proposed spatial measures are not good predictors of movement.

Table 2: NYC correlations with vehicle traffic (1388 counts)

	Walk^5 26 it.	Walk^5 300 it.	Walk^{10} 26 it.	Walk^{10} 300 it.	Nat St 30°	Nat St 75°	Choice 10k ft	Choice 20k ft	Choice rad n
Rank	0.25	0.33	0.26	0.40	0.46	0.45	0.20	0.32	0.37
log/log	0.30	0.37	0.35	0.45	0.45	0.46	0.19	0.27	0.33

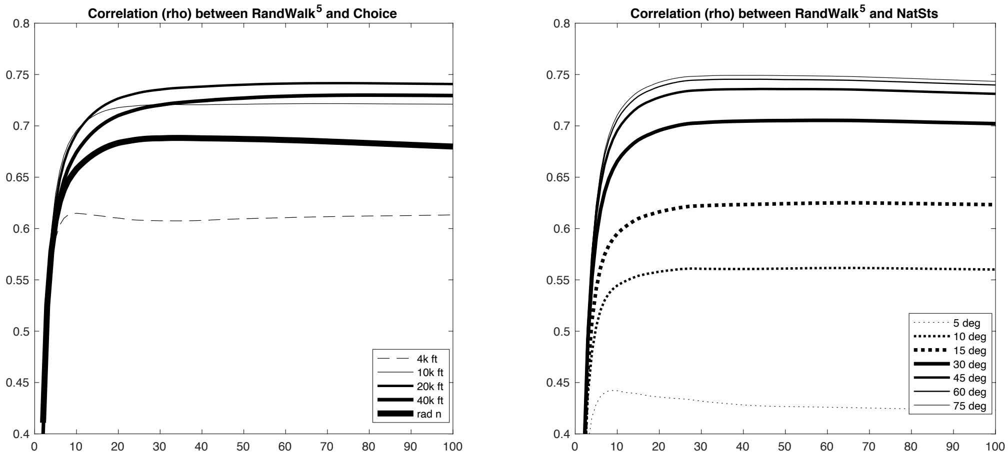

Figure 3: New York: locally defined Random Walks are well correlated with both non-local variables of Choice (left) and Natural Streets (right).

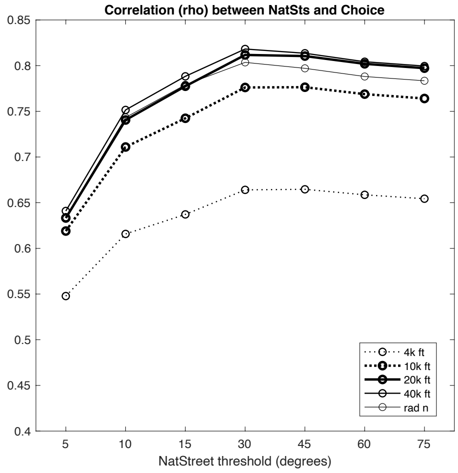

Figure 4: New York: Choice and Natural Streets are well correlated.

But how does New York rate in terms of intelligibility? As per figure 1 (also: Hillier et al 1987; Penn 2003; Zhang et al 2013) if intelligibility is the source of strong correlations between spatial variables found in cities like London, it might be expected that these poorer correlations arise because of a lack of relationship between local and global structure. Yet if we examine the correlations between the same measurements above, this does not appear to be the case. Figure 3 shows correlation values between random walks, based on highly localised information, and both natural streets and choice, which rely on increasingly longer-range information. For the parameters of each associated with the best prediction of movement, choice radius ≈20,000 ft and natural street threshold ≈30 to 75 degrees, correlations are in the range of $\rho \approx 0.74 \pm 0.01$. This is significantly higher than those between space and movement (Table 2) in New York and comparable to that found in London (Hanna 2021). By way of completeness, figure 4 plots the correlation between natural streets and choice, both relying on longer range information but in varying degrees. These two measures are also seen to correlate well (for the same parameters: choice radius ≈20,000 ft and natural street threshold ≈30°) with an even greater $\rho \approx 0.8 \pm 0.01$.

Table 3: Comparative values for Intelligibility, Predictability and Exosomatic correlations of figure 1, based on the angular measures used in this section. London traffic correlations are mean of both data sets used; London Intelligibility (*) is taken from value reported in Hanna 2021.

	Intelligibility (local-global)	Predictability (global-movement)	Exosomatic (local-movement)
London	0.72 (RandWalk^4, Choice4km)*	0.81 (Choice4km, veh)	0.79 (RandWalk^4, veh)
NYC	0.74 (RandWalk^5, Choice20kft)	0.32 (Choice20kft, veh)	0.37 (RandWalk^5, veh)

Table 3 compares the results for both London and New York, expressing the measures in this section as the relationships of figure 1: intelligibility, predictability and exosomatic potential. It shows that two cities which are both “intelligible” by this measure can result in very different patterns of movement, and so the expected relationship between intelligibility and predictability is not guaranteed.

In this context the high intelligibility of New York is surprising. This suggests that the correlation between random walks and choice found in London (Hanna 2021) is either (a) not the result of a particular optimisation of the grid to convey long range information to a navigator, but something more common, or (b) it is an optimisation found also in New York. The next section will try to assess just how rare such a property is by determining at finer level which types of networks are intelligible and which are not.

4 IMMEDIATE INTELLIGIBILITY AND LINK BETWEENNESS

Intelligibility measures provide a finer grained view of network structure than the aggregate distributions above by showing correspondence between local and global at individual locations within the city. In traditional intelligibility (Hillier et al. 1987; Hillier 1996; Penn 2003) the most local properties of an axial line, its length or degree, are already distributed over its length, and not always visible at a single point. To maintain consistency with the segment-based measures above, and to more closely assess the visual information actually available to an individual at any one point, this section introduces a new measure of intelligibility that assesses the long-range information available immediately at each intersection.

4.1 A new measure: immediate angular intelligibility

Axial intelligibility is the correlation between a local and a longer-range property of an axial line (connectivity and integration), but no direct equivalent properties can be found for individual segments. Instead, the measure introduced here is based on the same fundamental unit as each of the analyses above, which is the *angle between any two* segments. This angle is a local property clearly defined and directly visible to a real navigator within the network.

Angular choice (or betweenness) is a longer-range or global property strongly associated with both empirical observations of real movement and based on assumptions of overall route observation, and so can fill a role analogous to integration in axial intelligibility. The problem is that it is defined only at the segment, and not *between segments* as is angle.

Instead of the node betweenness of the graph, therefore, edge betweenness is calculated at the links between any two segments. Just as traditional node betweenness (or choice) is the ratio of all shortest paths within the graph (or limited radius) that pass through the given node, edge betweenness is the ratio of the same paths that pass through any given link. In the context of a navigator standing at a particular segment in a street network, facing a particular intersection, this has a real interpretation: assuming the network is filled with agents optimising their paths from every origin to every destination (for which we must assume perfect knowledge of the network), traditional node betweenness (choice) is a measure of the number of agents present on the current segment, and edge betweenness is the number of agents turning from this segment onto each of the adjoining segments, or vice versa. As such, it conveys information about the global or long-range structure of optimal routes and anticipated movement, but does so at a granularity that can be correlated directly with the local angle.

Both angle and edge betweenness are then normalised for each intersection. It is not the total number of agents deciding to turn left or right that matters, as this might differ significantly between the most populated segments and the least. Rather, for an agent standing facing any given intersection it is the probability of turning in each direction that is relevant. The value of edge betweenness is normalised by dividing by the total betweenness for all links associated with the given node (segment) in the given direction. Similarly, the angle values are divided by the sum of all angles leaving that segment in that direction.

The correlation between node-normalised angle and node-normalised edge betweenness yields the measure of *immediate angular intelligibility*. In this, the local property (angle) is immediately visible, and so more visually accessible to an agent at the particular location of the intersection than is the connectivity or length of the axial line used traditionally in intelligibility. The long-range property of edge betweenness may be any radius up to the global width of the map.

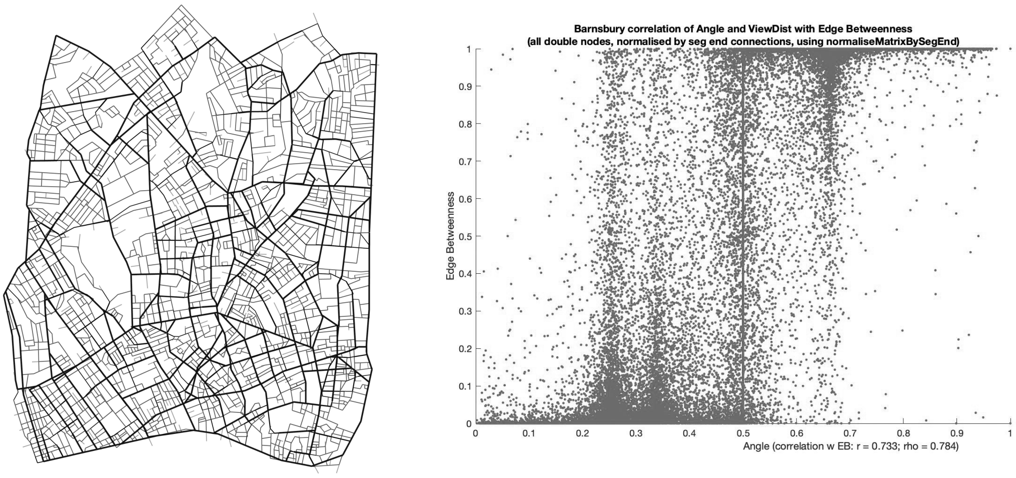

Figure 5: Barnsbury (left) and scatter plot of edge betweenness plotted against turn angle, normalised for each turn.

The Barnsbury neighbourhood in London, used in early studies of axial line intelligibility (Hillier and Iida 2005) illustrates this measure of immediate intelligibility (fig. 5). The scatter plot shows the angle at which every two segments meet in the horizontal axis and the associated edge betweenness in the vertical; both values are normalised by the total for that particular intersection. The scatter is difficult to read because of the density of points at particular angle values, and because of significant variation in edge betweenness throughout, but it is evident and notable that there is some structure resulting from the geometrical ‘griddedness’ of the network. The vertical bands correspond to right-angled turns of various configurations: turning left or right at a four-way intersection (at the normalised angle of 0.25); turning from (0.33) or remaining on the main road (0.67) at a T-junction; continuing straight at a four way or turning from the minor road at a T (0.5). The horizontal noise in these bands is due to the grids not being perfectly rectilinear.

The importance of this scatter is in the relationship between the two variables. While there is substantial noise in the edge betweenness axis, it is also evident that the normalised angles below 0.5 are chosen significantly less than those above 0.5. Quantifying this for the set yields a Pearson r=0.733 and the rank correlation ρ=0.784, these strong correlations suggesting a high intelligibility of Barnsbury. This agrees with previous studies by axial line measures; the traditional axial intelligibility (connectivity and integration) for the same map is a nearly identical r=0.746 if calculated using an axial radius of 3 (although this drops to r=0.454 using the global radius n).

4.2 Rectilinear grids and uniform segment topologies

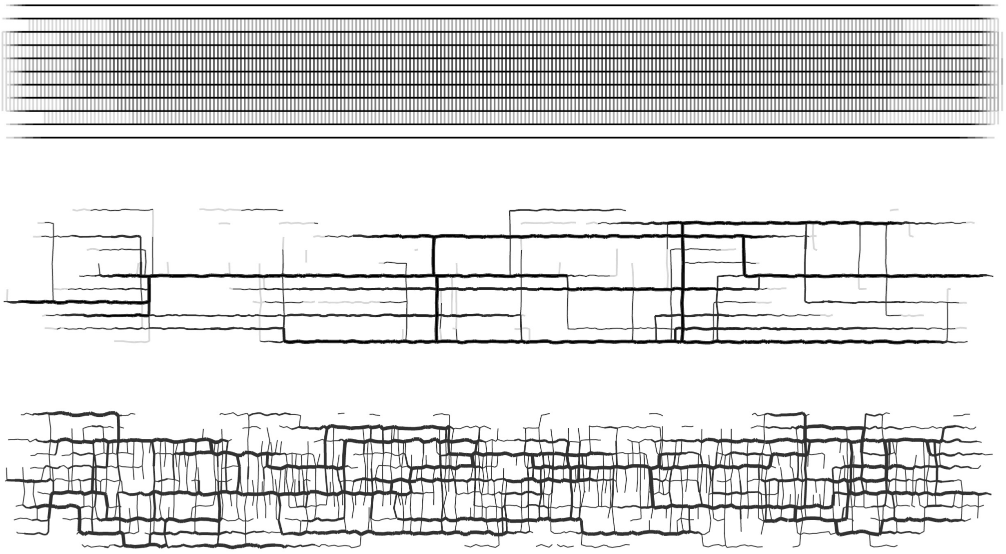

Figure 6: Regular grid of 80’ x 275’ blocks (top); the same with random perturbation of intersection points within 10% of the block distance (middle); and 20% of block distance (bottom). Each is topologically a full grid; only segments of highest choice values are shown here, demonstrating a marked hierarchy of “foreground” and “background” network exists with random perturbation, even if not intelligible.

The effect of the grid evident in figure 5 differs from the serious problem found in axial intelligibility. The problem in the latter case, with the global measure, is that topological centrality is equal everywhere on the grid: each line is exactly one step from every perpendicular street and exactly two steps from every parallel street. In immediate angular intelligibility the long-range measure of centrality does indeed vary throughout, resulting in higher values of choice for segments closer to the geometrical centre; this corresponds with our intuitive sense of centrality. What is similar between the two methods is the lack of variance of the local measure: just as each parallel axial line has the same length and connectivity, each segment intersection has an identical four right angles.

If we introduce noise into these angles by randomly perturbing the locations of the intersections of a grid, we find a corresponding change in the global structure of the network indicated by angular segment choice. Figure 6 (top) shows a perfect grid of 80' x 275' blocks, roughly based on Manhattan, with darker lines indicating higher global choice values (the lowest values of choice are invisible in the diagram, but exist), and indicating some gradual, symmetrical variance. By shifting each intersection point at random by a maximum of 10% (middle) and 20% (bottom) of the block size, the map becomes less grid-like at the local level. Despite this variance, axial intelligibility is still not a meaningful measure as the axial lines are now equivalent to segments and remain identical in terms of local connectivity. The variance is captured by the local angular and global choice measures of immediate intelligibility.

The perturbed grids (fig. 6 middle and bottom) show the emergence of a distinct hierarchy, with a foreground network of connected, high choice streets. By the angular route optimisation assumptions implicit in the measurement of choice, these should be routes of greatest traffic. For these near-grid networks to be intelligible at the level of the individual intersection, as Barnsbury, we should again expect to see local angle to be strongly correlated.

Figure 7 indicates they are not. Plots on the right are equivalent to that of Barnsbury (fig. 5), and show some correlation, but far less. The regular grid (top) suffers from the more extreme lack of variance in normalised angle due to its strict orthogonality, and yields a poor correlation of $\rho=0.261$. The two perturbed grids appear better to pick out some of their emergent foreground network, with correlations of $\rho=0.474$ and $\rho=0.498$ respectively, but these are still relatively low. Plots on the left display the true values for angle (0.0 is 180°, 1.0 is straight ahead) and (log) edge betweenness, not normalised by intersection, which better indicate the nature of the limited geometry. The only two types of turns, 'straight' or 'right angled' in the regular grid, become noisier in the perturbed versions. While the edge betweenness is generally higher for those going straight, the fact that the expanded clusters do not display a marked structure indicates this local noise is not particularly revealing of the emergent global structure. These correlation values are similar with $\rho<0.5$. Both measures indicate a lack of intelligibility compared with the real neighbourhood example of Barnsbury.

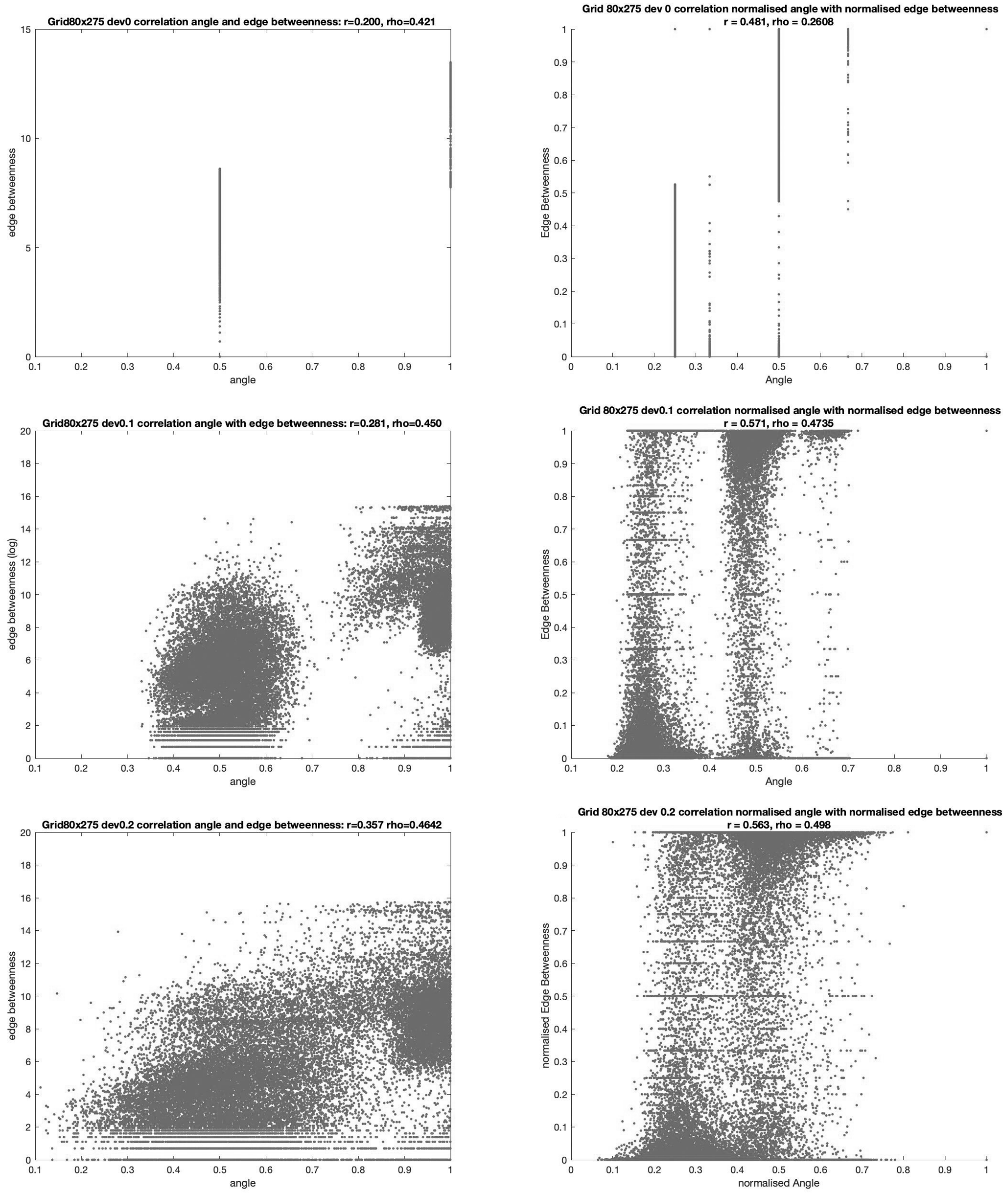

Figure 7: Scatter plots of edge betweenness against turn angles, actual values (left) and normalised for each turn (right).

4.3 Random network patterns

The question remains whether the intelligibility of the Barnsbury example is an outlier: an unusually optimal correspondence between local angle and long range routes that can be found in cities like London and New York, but is otherwise unlikely. This is tested using two randomly generated street networks of different types. The intent of these is as random samples representative of the large, unoptimized portion the space of possible graphs. Exhaustive studies of this set of all graphs is beyond the scope of this paper, and so is quantifying the likelihood of high intelligibility occurring, but these can help to indicate (if their intelligibility is low) that many arbitrary networks are likely to be poorly intelligible or (if high) refute the hypothesis that high intelligibility of Barnsbury and New York must be the result of a special optimisation of urban form.

The first (figure 8, left) is a collection of 1000 randomly placed lines, equivalent to axial lines, which overlap to form a network. Locations are a uniform random distribution in space, and lengths are normally distributed with a set upper bound; these are converted to a segment map by dividing at intersections and removing stubs. The second (figure 8, right) is the Delaunay triangulation of 2000 randomly spaced junction points. Delaunay triangulation results in an unrealistically high number of acute angles, so these are pruned by removing those that were longest lines on any two neighbouring triangles; as lines do not overlap it is already equivalent to a segment map.

Where the grids above (section 4.2) were intended as approximate analogues to Manhattan, these random networks resemble in rough order of magnitude the graph of Barnsbury. Barnsbury covers an area of approximately 2.4km x 3 km; its 1915 axial lines have a mean length of 130.1 m and maximum of 1336 m; resulting in 7269 segments of mean length 30.1 m and max. 197.3 m. The random line network covers a 2.5 km square with 1000 axial lines (mean 271.1 m and max 609.4 m) which results in 7660 segments with a mean length of 34.9 m and max length of 326.5 m. The triangulated network also covers a 2.5 km square, and results in 4698 segments (axial lines do not apply) with a mean of 59.8 m and maximum of 182.2 m.

The scatterplots indicating correlation between normalised local angle and global edge betweenness (figure 8, bottom) indicate a strong degree of immediate intelligibility, comparable to that of Barnsbury rather than the grid-based examples in section 4.2. There are notable differences in the detail of the scatter: a more horizontally continuous cloud in both is due to the more uniform distribution of angles; the foreground/background network distinction (vertical axis) is less pronounced in the triangulated network than both the random lines and Barnsbury; and the distribution is more compressed toward the left in the triangular grid due to the greater average number of segments meeting at each junction. But the values of correlation for each are similarly high, at $\rho=0.801$ ($r=0.719$) for the random lines and $\rho=0.749$ ($r=0.684$) for the triangulated network.

As is the case with the randomised grids above (section 4.2) traditional axial intelligibility is not meaningful in the case of the triangulated network (as all axial lines are identical to segments), but it can be calculated for the network of random lines. As in the case of Barnsbury, above, the values are comparable to those given here by immediate angular intelligibility when calculated for axial radius 3, $r=0.865$, and drop to $r=0.403$ for the full graph radius n.

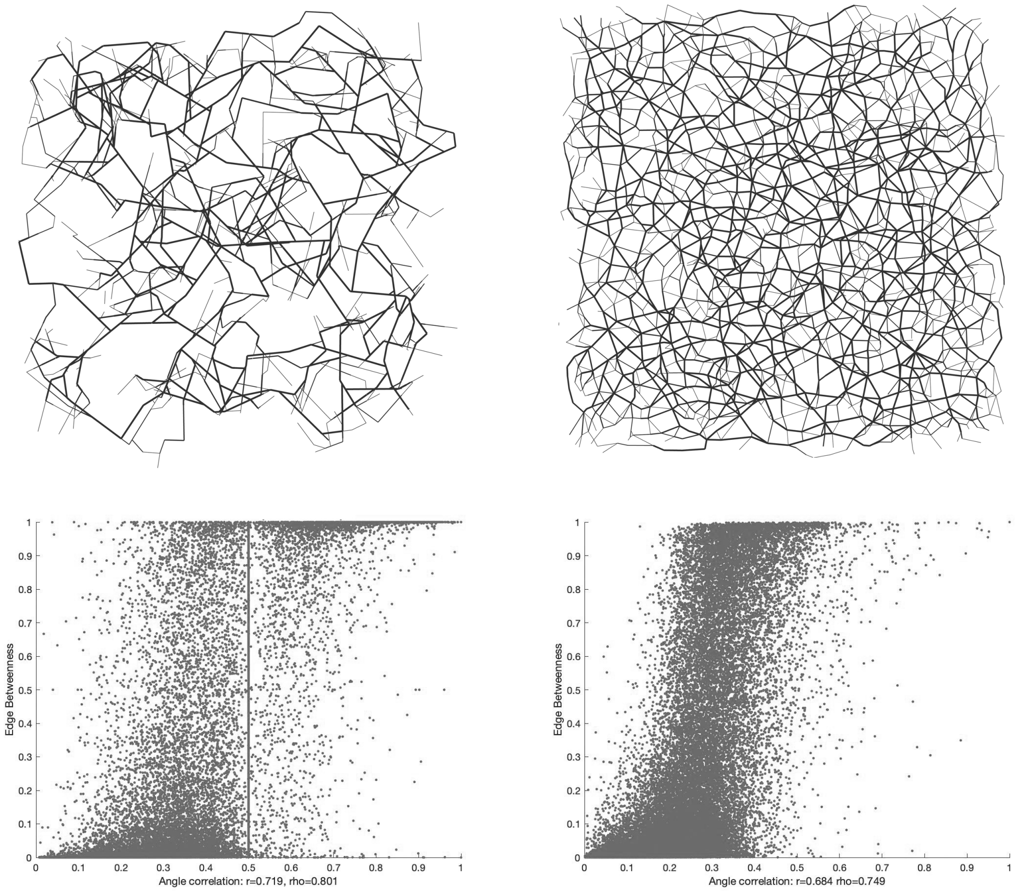

Figure 8: Street networks and scatterplots of immediate angular intelligibility for a random line network (left) and random triangulated network (right).

5 CONCLUSIONS

Despite intelligibility previously being defined only as a topological measure, this paper has demonstrated it can also be applied to geometry. Empirical evidence for the similarity between previous topological and the demonstrated geometrical methods (esp. section 4.1, also 4.3, 3.2) support the claim that topological representations internalise geometry into the graph (Hillier 1999), so are describing equivalent phenomena. The additional relationship, both theoretically and in observation, between angular measures across local to global scales (sections 3 and 4) argue against claims that any particular measure is superior to another, and may help to reconcile strands of research separated by these distinctions.

Immediate angular intelligibility is a methodological contribution. It has the practical advantages of corresponding to methods of representation used in segment-based analysis, of being definable at a finer level of local resolution, and of being applicable to networks (such as grids) for which axial intelligibility is not. It has the theoretical advantage that turn angle is a property directly and immediately perceptible at decision points by real navigators in the grid, whereas axial connectivity may not be, and thus mirrors a plausible exosomatic navigation model (as: Turner and Penn 2002; Hanna 2021). Initial results indicate it yields similar values to axial intelligibility.

It can be observed that there is a particular scale range corresponding best to non-local movement. The scale of the non-local could refer to anything up to the entire network, although peaks are seen in both correlations between non-local measures and observed traffic, and between one another: around the 4 km radius in angular choice; around 26 iterations of a random walk (section 3). Despite observations that some properties of cities are scale-free (Jiang 2009), this agrees with assumptions implicit in previous uses of axial intelligibility, which appears most evident at a similar non-local scale e.g. axial radius 3 (Penn 2003). The fact that this scale is found in relationships between spatial measures (random walks, natural streets, angular choice: section 3.2 figures 3,4) independently of movement, even in a city with poor movement predictability, indicates this is not just an artefact of human behaviour but a feature of the networks. Immediate angular intelligibility (section 4) was tested using a global measure (whole-graph choice), but used neighbourhoods of a scale of 2–3 km (the scale of grids in section 4.2 were approximately 6.4 km x 838 m, so comparable in area); this is similar order of magnitude to the same scale (radius 4km) which corresponds best to human movement, so it is likely to pick out the same non-local structure. It seems plausible (as e.g. Hanna 2021) that this scale is related to the length of a typical journey, although more detailed study would be required to determine this relationship.

These analyses partly answer the question of the likelihood of intelligibility. Is it unlikely to have “evolved by chance” (Hillier 1999)? Are real urban networks a rare subset of graphs particularly well optimised to convey structural information to the navigator (Hanna 2001)? Results stop well short of an exhaustive analysis of all possible networks, but show strong correlations between immediate angular information (individually or within random walks) and non-local route structure (choice) both for (a) actual cities, of both high (section 3.1) and low (section 3.2) movement predictability, and (b) randomly placed streets (section 4.3). Both give counterexamples to implied assumptions and suggest the property of intelligibility may be much more common than expected. The examples of random streets (section 4.3) indicate that intelligibility may be a likely outcome of composing straight streets within a 2-dimensional plane. However, the correlations are not universal, and break down in certain graphs, including regular grids and those approaching regular grids. The use of immediately visible information as a means to navigate may thus be valuable within ‘organic’ cities and a wide range of other geometries, but not all.

At the level of individual perception, both angular weighted random walks (section 3) and immediate angular intelligibility (section 4) model intelligibility at a level that is a plausible mechanism for exosomatic navigation. Immediate access to information, requiring no memory of movement over time to form an explicit or intuitive model of structure (as e.g. Hillier et al 1987;

Figueiredo and Amorim 2005; Jiang et al 2008) but also requiring no distant visual input (Hillier 1996; Penn 2003) is consistent with observation and with the mechanism in the simplest random walk models (Turner and Penn 2002; Hanna 2021), indicating support for the exosomatic hypothesis.

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