

Article

The Legibility and Permeability of Cities: Examining the Role of Spatial Data and Metrics

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Abstract: It has been long recognised that the underlying spatial structure plays an important role when navigating in urban environments. However, the modelling of the forms and properties that emerge from the city is still a difficult issue to address. The objective of the research developed in this paper is to study and represent two important qualities of urban environments as identified by Lynch and Bentley in their respective seminal works, that is, legibility and permeability. Our objective is to identify and implement a series of metrics applied to the layout of a given city that reflects these concepts of legibility, and then to evaluate to which degree these measures are correlated to different human perceptions of the city, particularly differences between humans who have or have not had an experience of a given urban environment. The whole approach is applied to the context of a neighbourhood of the city of Tehran in Iran. The findings show that permeability match relatively well with residents' evaluations while legibility rather complies with newcomers' evaluations.

Keywords: urban form; legibility; permeability; spatial metrics; human perception

1. Introduction

The act of navigation in an urban environment is one of the subjects that are closely influenced by the spatial configuration of the environment [1–4]. In particular, it was observed that people's initial exploration of an urban environment is partly shaped by local spatial properties [5]. On the other hand, humans that have a previous knowledge or have experienced a given environment are more likely to rely on global spatial properties rather than local ones [5]. Penn suggests that in familiar environments, way finding tasks are relatively independent of local properties and are instead largely driven by global properties of the spatial structure of an urban space [6]. Overall, further evidence for the role of spatial configurations in navigation processes has been largely studied particularly by space syntax research [7].

Legibility has been considered to be one of the main desirable qualities of navigation in urban environments [8,9]. The notion of legibility has been introduced by Lynch in a seminal work as the ease with which the parts of the city can be recognized and organized into a coherent pattern [8]. Bentley et al. categorizes the concept of a responsive urban environment via seven levels amongst them legibility and permeability [10]. Permeability is the property that denotes the ability to sense or move through a given environment [11]. It is largely influenced by the available paths and forms that emerge from a given urban space [12]. Overall, legibility and permeability provide key indices for evaluating urban navigation capabilities in the city [13–17]. However, and despite the fact that

these two concepts can be intuitively understood, their computational evaluation is far from being a straightforward task and has been hardly addressed in recent work.

The objective of the research presented in this paper is to explore and develop a computational approach that can provide an assessment of the legibility and permeability of the urban layout, as well as their respective roles in the evaluation of navigation capabilities in an urban system. We model an urban layout as a sort of bird's eye view on an urban space, where buildings, paths and open spaces are the main spatial components considered. An important property of an urban layout is that it can be abstracted and represented within a computational GIS representation upon which different spatial measures are computed and derived. The first challenge is to identify and compute a set of spatial metrics from the layout of a given city, while the second one is to find to which degree the developed measures match people's perceptions and own evaluations. The latter follows a hypothesis discussed by Hillier and that states "the organic as well as the geometric, are pervasively ordered by geometric intuitions" [18]. In particular, we will make a difference between human beings that have or have not previous knowledge of a given urban environment (denoted in the rest of the paper as residents and newcomers, respectively).

The metrics developed are partly derived from geometric properties also applied elsewhere in landscape ecology [19] and that have shown potential for analysing urban morphology [20–24]. We complement these geometric-based metrics by a series of alignment, continuity and symmetry indices that reveal some additional properties of the urban layout. The whole approach is applied to a neighbourhood of district 12 in the city of Tehran in Iran. The emerging results are compared to people's perception and opinions coming from either residents familiar with a given urban environment or newcomers with no prior knowledge of that urban environment. The preliminary experiments and findings show that the introduced measures of permeability comply relatively well with inhabitant's perception, while the measures of legibility rather match newcomers' perception.

The remainder of the paper is organized as follows. Section 2 briefly surveys related work while Section 3 develops the notions of legibility and permeability and the main spatial and geometrical properties developed for the representation of an urban layout. Section 4 develops an application of the modelling concepts developed to a case study and a series of experimental evaluations. The findings are evaluated and discussed in Section 5. Finally, Section 6 summarizes the paper and outlines future works.

2. Related Work

Over the past few years, the influence of the urban layout on navigation tasks has been studied by several researchers. In particular, the impact of different urban designs on walkability have been explored [25]. Similarly, different building structures have been considered as a discriminant factor when planning navigation tasks [26]. From a different perspective, the role of salient features have been also identified as important properties in the execution of navigation and way-finding processes [27]. Overall, it clearly appears that the underlying local and global structural properties of a given urban environment shape cognitive representations [28]. In particular, recent agent-based computational approaches that replicate navigation tasks demonstrate that modelling performances improve when considering the scenic layout [29], visual properties play indeed a significant role in shaping the perception of a given urban environment and then navigation opportunities [30]. At the local level, differences and commonalities between expert-based and resident-based perceptions of a given built environment have been also investigated [31]. A few attempts have been also oriented to comparison between humans' perception of a given urban environment and quantitative representations of a built environment [31,32].

Our research has a specific focus on the concepts of legibility and permeability as introduced and characterized by Bentley et al. [10] and Lynch [8], respectively. In fact, a search for a better understanding of humans' learning processes in built environments is still a non-straightforward task. This is partly due to the fact that legibility is closer to a subjective category rather than an objective

spatial property [33]. In particular, the notion of legibility has been modelled by Long et al. [32], while permeability, considered as a measure of movement opportunity is more related to a sense of enclosure in a given environment [13,15]. The findings suggest that space syntax can provide computational measures to quantitatively represent the concept of legibility using a measure of intelligibility. Our research will go further by first providing a set of quantitative measures that compute and evaluate the notion of legibility and permeability at different degrees using topological and directional primitives, as well as visual properties of the urban layout as suggested in [34]. A second objective of our research is oriented to the study of how these measures reflect humans' own perception. Overall, this paper introduces and provides a set of computational and flexible measures of legibility and permeability as introduced by Lynch and Bentley, and reviews how they map and to which degrees humans' perceptions.

3. Modelling Approach

This section studies and discusses the spatial structure of an urban layout using the notions of legibility and permeability. The parameters developed are formally presented and have been computationally implemented. Figure 1 summarizes the spatial metrics used for the modelling of the legibility and permeability parameters introduced in the next sub-sections, and the interpretation process as reflected by human beings familiar or unfamiliar with a given urban environment.

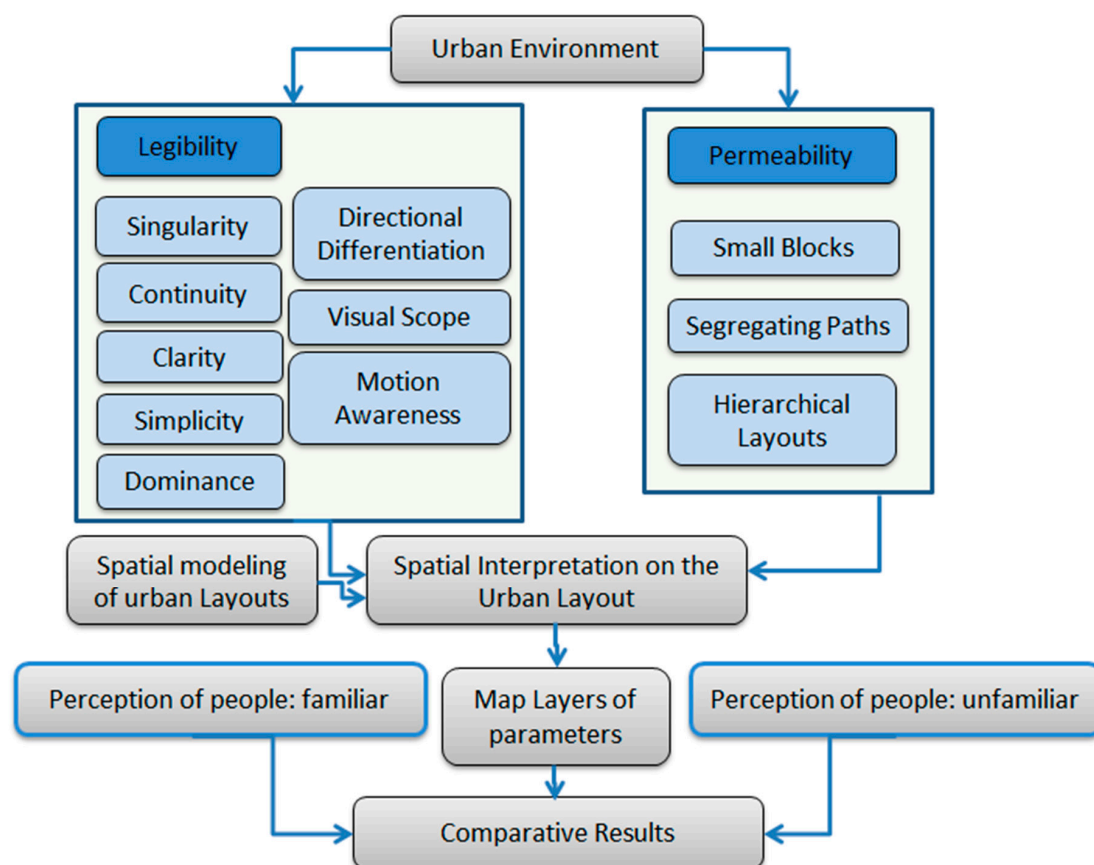


Figure 1. Modelling and computational approach principles.

3.1. Legibility

Legibility can be defined as the ease with which the parts of the city can be recognized and organized into a coherent pattern. A legible city would be one in which districts or landmarks or pathways are easily identifiable and structured [8,10]. In his seminal work, Lynch identified the main

forms and qualities that emerge from an urban layout. Such categories contribute to the visibility, coherence, clarity and then the legibility of an urban environment [8] (Table 1).

Table 1. Lynch’s legibility qualities.

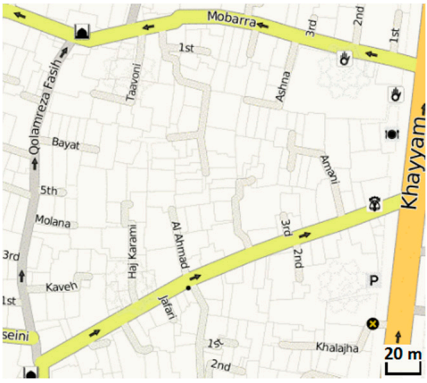
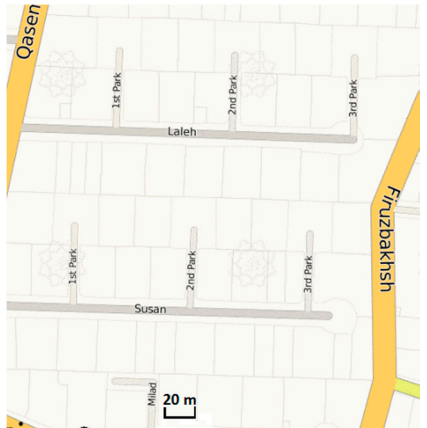
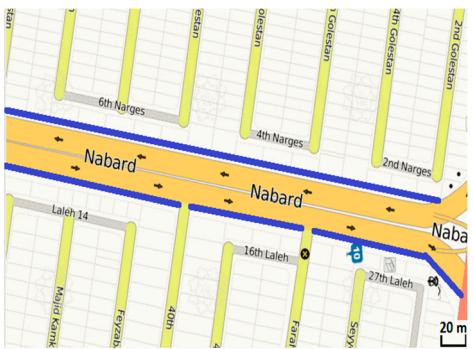
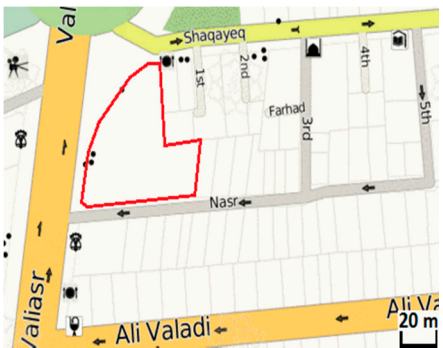


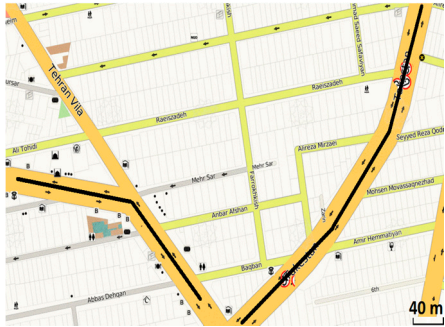

Qualities	Examples
<p>Singularity: Singularity denotes the contrast and distinguishability of urban objects in a given scene [8]. This is illustrated by the relative high singularity of the parcels that appear in the Khayyam neighbourhood in Tehran.</p>	 <p>A map of the Khayyam neighbourhood in Tehran. The map shows a grid of streets with several parcels highlighted in yellow. These parcels are irregular in shape and size, contrasting with the surrounding regular grid. The streets are labeled with names like Mobarra, 1st, 3rd, 2nd, 1st, 5th, Molana, Bayat, Tavoni, Ashna, Rami, Kaveh, Haj Karimi, 1st, 2nd, 3rd, 4th, 5th, 6th, 7th, 8th, 9th, 10th, 11th, 12th, 13th, 14th, 15th, 16th, 17th, 18th, 19th, 20th, 21st, 22nd, 23rd, 24th, 25th, 26th, 27th, 28th, 29th, 30th, 31st, 32nd, 33rd, 34th, 35th, 36th, 37th, 38th, 39th, 40th, 41st, 42nd, 43rd, 44th, 45th, 46th, 47th, 48th, 49th, 50th, 51st, 52nd, 53rd, 54th, 55th, 56th, 57th, 58th, 59th, 60th, 61st, 62nd, 63rd, 64th, 65th, 66th, 67th, 68th, 69th, 70th, 71st, 72nd, 73rd, 74th, 75th, 76th, 77th, 78th, 79th, 80th, 81st, 82nd, 83rd, 84th, 85th, 86th, 87th, 88th, 89th, 90th, 91st, 92nd, 93rd, 94th, 95th, 96th, 97th, 98th, 99th, 100th. A scale bar indicates 20 m.</p>
<p>Simplicity: Simplicity characterises the geometrical forms of an urban layout. Simple forms in an urban layout are likely to favour a better perception and understanding of the environment [8]. The figure to the right presents an area that exhibits regular and simple forms of the parcels (Kashanak neighbourhood).</p>	 <p>A map of the Kashanak neighbourhood. The map shows a grid of streets with several parcels highlighted in yellow. These parcels are rectangular and have regular shapes, contrasting with the surrounding irregular grid. The streets are labeled with names like Qasen, 1st Park, 2nd Park, 3rd Park, Laleh, 1st Park, 2nd Park, 3rd Park, Susan, 1st Park, 2nd Park, 3rd Park, Milad, 20 m. A scale bar indicates 20 m.</p>
<p>Continuity: Continuance characterises the edges of an urban layout. A continuous edge should visually extend the potential perception of an urban space [8]. The figure to the right presents an example of continuity edge to the North, while there is a breakdown of continuity close to a street intersection to the South.</p>	 <p>A map showing a street intersection. The map shows a grid of streets with several parcels highlighted in yellow. The parcels are rectangular and have regular shapes. The streets are labeled with names like Nabard, 6th Narges, 4th Narges, 2nd Narges, Laleh 14, 16th Laleh, 27th Laleh, Farah, Seyy, 20 m. A scale bar indicates 20 m.</p>
<p>Dominance: Dominance denotes the property of a given urban feature with respect to the others in its neighbourhood [8]. The figure to the right shows a parcel very much different from the others in the neighbourhood.</p>	 <p>A map showing a parcel highlighted in red. The map shows a grid of streets with several parcels highlighted in yellow. The parcel is rectangular and has a regular shape, contrasting with the surrounding irregular grid. The streets are labeled with names like Val, Shafayeh, 1st, 2nd, 4th, 5th, Farhad, Nasr, Ali Valadi, 20 m. A scale bar indicates 20 m.</p>

Table 1. Cont.

Qualities	Examples
<p>Clarity of intersections: Street intersections are strategic places of an urban layout and should be highly perceptible [8]. Paths in a layout with low directional discrepancy are likely to exhibit a low clarity of perception. The figure to the right exhibits an example of such low clarity.</p>	 A map showing a complex intersection in Tehran. A main road runs vertically, with several side streets crossing it. The streets are labeled with Persian names. A blue line highlights a path through the intersection, showing how the layout might be confusing. A scale bar indicates 20 meters.
<p>Directional differentiation: Directional differentiation denotes asymmetries of urban streets. For instance, asymmetries revealed by radial differences of urban streets can obscure the sense of direction [8]. The example shown in the figure to the right by the Navvab highway exhibits a case whose symmetric sides obscure the sense of direction.</p>	 An aerial photograph of a wide, multi-lane highway in Tehran. The highway is flanked by dense residential buildings on both sides. The symmetry of the urban layout on either side of the highway makes it difficult to distinguish direction. A scale bar indicates 20 meters.
<p>Visual scope: The visual scope reflects the range and penetration of the vision in a given street [8]. The example illustrated by the figure to the right shows the Sattarkhan and Takestan Streets in Tehran whose bends limit the perspective offered.</p>	 A map showing a street layout in Tehran. A main road runs diagonally, with several side streets crossing it. The streets are labeled with Persian names. A blue line highlights a path through the intersection, showing how the layout might be confusing. A scale bar indicates 40 meters.
<p>Motion awareness: Motion awareness denotes the qualities sensible to the observer, through visual and the kinaesthetic senses, and that constrains motion. Motion awareness is for instance impacted by curves and direction changes that constrain the visual scope [8]. The example to the right presents the bendiness of Allameh Jafari street in the Tehran that constrains motion.</p>	 A map showing a street layout in Tehran. A main road runs diagonally, with several side streets crossing it. The streets are labeled with Persian names. A blue line highlights a path through the intersection, showing how the layout might be confusing. A scale bar indicates 200 meters.

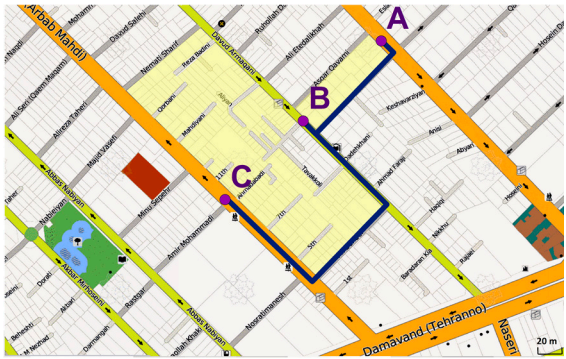


Two additional qualities have been suggested to complement the above mentioned eight qualities, that is, “time series” and “names and meanings” [8]. A time series reflects a melodic sequence of

image elements or a formed succession of space, texture, light or silhouette. Names and meanings are non-physical characteristics that enhance the imageability of a given urban element. Both of these parameters are relatively subjective and are not closely related to geometric interpretation in urban environments and hence have not been considered in this work.

3.2. Permeability

Permeability is defined as a visual and behavioural quality that reflect both seeing and moving opportunities in a given urban environment [34]. A given network area is considered very permeable to cycling if it allows to connect any two of its nodes, back and forth [35]. Bentley et al. (1985) studied the notion of permeability in an urban environment and suggested three design trends that should positively influence the layout of cities and then physical and visual permeability [10]. These include the search for small blocks, avoiding segregated paths and hierarchical layouts as introduced in Table 2.

Table 2. Design trends that favour a permeable layout.

Design Trends	Examples
<p>Small blocks: Small blocks offer a higher sense of permeability by offering additional and generally short route alternatives to choose from as. As it can be seen in the example to the right, the Euclidean distance between locations A and B are equal to the distance between points B and C. However, the path between A and B is shorter than the path between B and C. This is due to an important difference in the size of the blocks that are situated between these pairs of locations.</p>	
<p>Segregating paths: Segregating paths can be achieved by segregating transportation opportunities in the urban network, for example by specialising different network categories such as private vehicle, public transportation and motorcycle users [10]. Segregated paths have limited potential in passing through and consequently have less permeability. The figure shows the Vali-e-Asr Street in the Tehran that is segregated to a path for buses and a one way path for vehicles. This leads to heavy traffic in the middle of Tehran as shown in the picture but better traffic performance for public transportation.</p>	
<p>Hierarchical layouts: A hierarchy layout denotes an urban network designed at different levels of granularity. As illustrated in the figure to the right, hierarchical layouts generate cul-de-sacs and less route opportunities and then less permeability [10], but a probable sense of security to the inhabitants.</p>	

3.3. Urban Layout

The main objectives of our research are first to identify the main urban structural components, and secondly to specify a series of spatial parameters that quantitatively evaluate urban forms. Practically, the approach is developed on top of an urban and spatial database that intrinsically models and supports the representation of urban features and the spatial relations (i.e., topological and directional) and metrics that emerge from the layout. The spatial structure of an urban layout is modelled as a sort of bird's eye view where buildings, paths and open spaces are the main spatial components considered. Nodes, landmarks, districts, paths and edges, as introduced by Lynch [8], are the main components that influence the individual's perception of an urban environment. Figure 2 illustrates the spatial layout of the studied area in the district 12 of the city of Tehran. In particular, parcels and paths are generated from cadastral maps at the scale of 1:2000. When considering the usual physical layout of a city represented by a spatial database, paths and parcels are almost all explicitly represented, while in this research we complement them by three additional abstractions: edges, blocks and districts. Paths are the streets and all channels in which people travel in the city, and usually perceive the city while moving through and along them [8] (Figure 2b). When moving in the city, people perceive edges, that is, boundaries such as wall, buildings and shorelines, that appear as lateral references and barriers (Figure 2d) [8]. Edges are generated from block boundaries materialised as vertices and connected as straight line segments, and then mapped towards straight line segments when aligned to unit edges [36]. A parcel is one of the structural well-defined abstractions that have separate land use or ownership title and are explicit in an urban layout (Figure 2a). A block is a set of adherent parcels that is isolated by the paths surrounding it (Figure 2c). Unlike blocks that are typically materialised on one side of a surrounded path only, the notion of district as identified by Lynch has been also considered. Lynch's districts are defined as two-dimensional features materialised by some identity or character not directly perceivable and not always directly perceivable from the spatial layout. The notion of district is in this work directly mapped to administrative units that emerge from the case study in the district 12 of the city of Tehran.

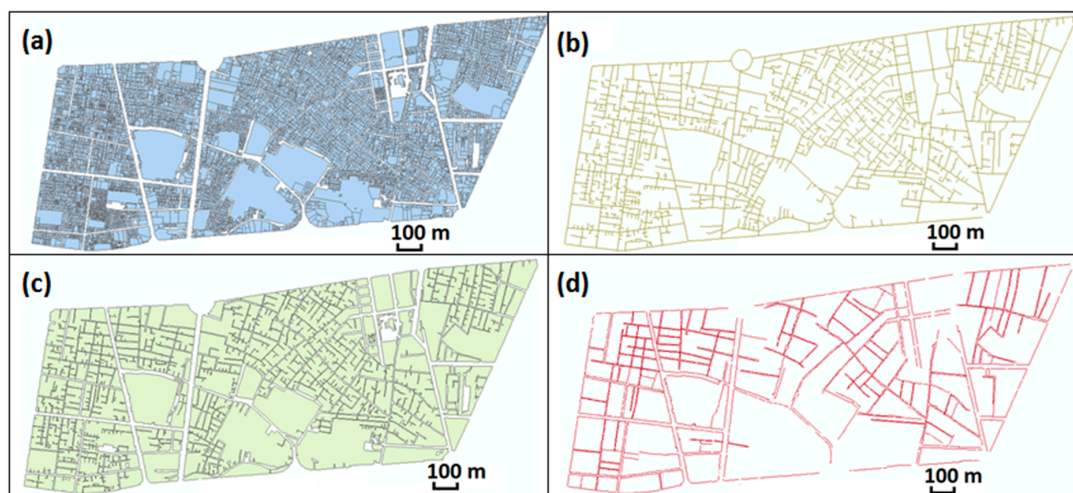


Figure 2. Urban layout of Tehran district 12: (a) parcels that have separate land use or ownership title; (b) paths; (c) blocks that are isolated by the paths surrounding them; and (d) edges.

The experimental evaluation of our research has been conducted with a study area related to a neighbourhood, located in the central part of Tehran, and that covers an area of about 3 km² (Figure 3) [35]. This neighbourhood is well known locally as it is a crowded area of Tehran's bazaar and contains a relative diversity of human activities and land uses.

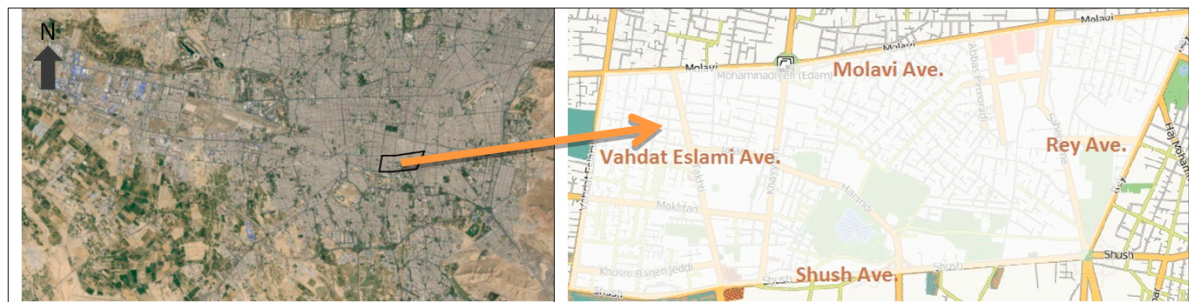



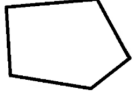

Figure 3. District 12 of the city of Tehran.

3.4. Evaluating an Urban Layout

All the components of an urban layout can be characterized by different spatial and non-spatial measures, whether the objective is to study the spatial or semantic properties of the layout. For instance, parcels can be described by some geometrical and qualitative spatial properties (e.g., area, perimeter, area/perimeter ratio, adjacency relationships) as well as by some non-spatial attributes (e.g., land use, type and age of building if any in the parcel). Since our research is oriented to the spatial analysis of an urban layout, non-spatial semantic properties will be omitted at this stage.

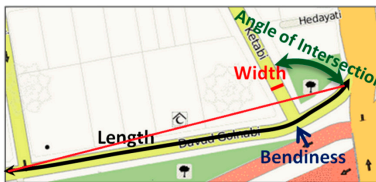
An objective of our research is to identify the spatial and mereology (i.e., part-whole relationships) measures that characterize the geometry and configuration of the different elements of an urban layout. The developed geometric measures evaluate the shape, size and relative position of the main components of an urban layout. Some of the identified measures are derived from landscape metrics [19]. They reflect the main spatial characteristics of the landscape layout represented as parcels, blocks and districts. These measures have been widely used in urban studies [20,21,37,38]. The metrics considered hereafter are those that quantify the spatial configuration of some urban components using different metrics and statistics [39,40]. A useful metric that measures the complexity of a parcel compared to a standard shape is SHAPE [40]. According to this metric, SHAPE_SD gives the standard deviation of parcels' SHAPE in a considered extent such as a block or a district. The statistical measures identified for the different metrics identified are mean (MN), range (RA), standard deviation (SD) and coefficient of variation (CV). Table 3 mathematically and geometrically introduces the landscape metrics introduced as spatial measures of the components of an urban layout.

Table 3. Selected landscape metrics used to evaluate urban layout components [40].

Landscape Metric	Definition	Illustration
Parcel Area: <i>AREA</i>	$AREA(p)$ denotes the area of a parcel p .	
Parcel Perimeter: <i>PERIM</i>	$PERIM(p)$ denotes the perimeter of a parcel p .	
Perimeter/Area: <i>PARA</i>	$PARA(p)$ denotes the Perimeter-Area ratio, it is given as follows: $PARA(p) = PERIM(p)/AREA(p)$	
Shape Index: <i>SHAPE</i>	$SHAPE(p)$ denotes the complexity of the shape of a parcel p . Shape complexity characterises the geometry of a given parcel, whether a parcel tends to be simple and compact, or irregular and convoluted. $SHAPE(p) = 0.25PERIM(p)/\sqrt{AREA(p)}$	
Number of Core Areas: <i>NCA</i>	$NCA(p)$ denotes the number of disjoint core areas of a parcel p based on specified edge depths. It is given by the number of internal zones generated by the application of a buffer function with a negative depth.	

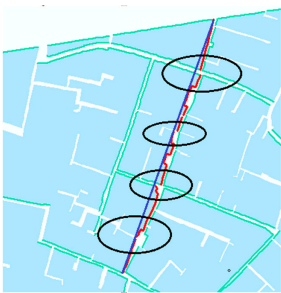
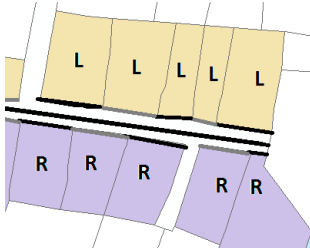
The metrics above are applied to parcels and then areal features, they can be used to characterise parcels and even blocks and districts. They have been all implemented in the ArcGIS software either directly using existing functions or using a combination of such functions. In order to complement these measures, we introduce and apply a few additional geometric measures that characterise paths in a layout (Table 4).

Table 4. Geometric measures applied to urban paths.

Geometric Measures	Definition	Illustration
Path-Length: PL	$PL(pa)$ denotes the length of a path pa .	
Path-Width: PW	$PW(pa)$ denotes the width of a path pa .	
Path-Bendiness: PB	$PB(pa)$ denotes the bendiness of a path pa . It is derived by the difference between the length of a path (i.e., black line) and the Euclidean distance between the first and end points of the path (i.e., red line) as illustrated by the Figure to the right.	
Angle of the intersection of two paths pa_1 and pa_2 : ANG	$ANG(pa_1, pa_2)$ denotes the angle in the intersection between two given paths pa_1 and pa_2 .	

Next, we introduce a series of configuration-based measures that essentially denote the arrangement, connectedness and continuity of urban components along paths (Table 5).

Table 5. Configuration-based measures used to measure urban layout components.

Topologic Measure	Description	Illustration
Alignment: ALT	$ALT(egd, p_1, p_2, \dots, p_n)$ denotes the alignment of a set of parcels (p_1, p_2, \dots, p_n) along an edge egd . It is given by the ratio of the length of that edge (e.g., the red polyline) to the distance between the endpoints of the edge (e.g., the blue line).	
Continuance: $CONT$	$CONT(egd, pa_1, pa_2, \dots, pa_n)$ denotes the relative continuity of the blocks along an edge egd (an outer boundary of the aligned blocks). It is given by the inverse of the number of intersecting paths pa_1 to pa_n (e.g., the ellipses in the figure to the right) along that edge.	
Symmetry: SYM	$SYM(pa)$ denotes the symmetry given by analysing the parcel boundaries along each side of a given path pa . This measure of symmetry is given by the ratio of the difference between the highest to the lowest (range) and mean of parcels boundaries (e.g., black and gray lines on each side of the path), to the right by the similar value to the ones to the left of a path pa . In the example given to the right, the number of parcels to the right is equal to the number of parcels to the left, but different parcel boundary ranges and means slightly alter the sense of symmetry of that path.	

A few other spatial measures have been suggested by space syntax theory to computationally investigate the shape and configuration of the environment [7,41]. However, space syntax measures do not directly evaluate urban forms, but instead provide some quantitative evaluations of the overall and local configurations of an urban structure based on network spatial analysis. For these reasons, they are not integrated as background measures of this research. Since the aim of this research is to consider the potential of spatial data and metrics when evaluating the legible and permeable properties of urban environments, the following sections refine and extend the computational measures identified in this section towards the qualities that play a relevant role in doing so.

3.5. City Legibility Computation and Interpretation

This section first revisits city legibility qualities as introduced in Section 3.2 and interprets them using the spatial measures introduced in Section 3.4. Such interpretations are computationally implemented as shown in Table 6. Overall, these measures should contribute to the exploration of the relationship between the forms, legibility and permeability of the city.

- Singularity: The contrast that appears from parcels' shapes give a sense of singularity to a given layout. For instance, when the coefficient of variation (CV) derived from parcels' shape and as given by the measure SHAPE (cf. Table 3) is high enough in a given layout, one might expect to have a few singular parcels in the considered layout. Form Simplicity: The *SHAPE* parameter denotes the complexity of a shape and can be used to evaluate the simplicity of a set of parcels in a given area.
- Continuity: The continuance *CONT* parameter (cf. Table 5) gives the degree of continuity of an edge in its urban layout.
- Dominance: The concept of Dominance can be revealed by different spatial measures. First, in an urban layout a low coefficient of variation (CV) derived from parcels' area (*AREA_CV*) is likely to exhibit a high degree of similarity and thus a lack of dominant parcels. In contrast, a significant difference between the maximum and minimum of the parcels' area (*AREA_RA*) in a given urban layout can rather denote the existence of some conspicuous parcels' size.
- Clarity of intersection: paths in a layout with low directional discrepancy (cf. angle of intersection in Table 4) are likely to exhibit a low clarity of perception. Instead, and for example, intersections with angles (*ANG*) between 70 and 110 degrees are likely to reveal a relative clarity of intersection [42].
- Directional differentiation: The Symmetry parameter *SYM* (cf. Table 5) directly measures this quality.
- Visual Scope: Unaligned edges as revealed by the parameter *ALG* (cf. Table 5) and paths with bends as evaluated by the measure *PB* (cf. Table 4) limit the vision scope.
- Motion Awareness: The bendiness of paths as given by the parameter *PB* is the parameter that gives a sense of possible motion.

Table 6. Qualities forms and computational rules.

Form Qualities	Computation Rules
Singularity	An urban layout, is considered to be a singular one if \forall District $d \in \text{Environment} \Rightarrow \text{SHAPE_CV}(d)$ gives a relative high value
Form Simplicity	An urban layout, is considered has reflecting Simplicity if \forall Parcel $p \in \text{Environment} \Rightarrow \text{SHAPE}(p)$ gives a relative low value
Continuity	An urban layout, is considered has reflecting a high degree of Continuance if \forall Edge $edg \in \text{Environment} \Rightarrow \text{CONT}(edg)$ gives a relative high value
Dominance	An urban layout, reflects some Dominance trends if \forall District $d \in \text{Environment} \Rightarrow \text{AREA_CV}(d) \in$ gives relatively a low value $\wedge \text{AREA_RA}(d)$ gives a relative high value
Clarity	An urban layout, is considered has reflecting clear intersections if \forall path $pa_1, \text{ path } pa_2 \in \text{Environment} \Rightarrow [\sim \text{Intersection}(pa_1, pa_2)] \vee \cap [70^\circ < \text{ANG}(path_1, path_2) < 110^\circ]$
Directional Differentiation	An urban layout, has clear Directional Differentiation if \forall path $pa \in \text{Environment} \Rightarrow \text{SYM}(pa)$ gives a relative low value
Visual Scope	An urban layout, has a clear Visual Scope if \forall edge edg and parcels $p_1, p_2, \dots, p_n \in \text{Environment} \Rightarrow \text{ALT}(edg, p_1, p_2, \dots, p_n)$ gives a relative high value
	An urban layout, has a clear Visual Scope if \forall path $pa \in \text{Environment} \Rightarrow \text{PB}(pa)$ gives a relative low value
Motion Awareness	An urban layout has a high value of Motion Awareness if \forall path $pa \in \text{Environment} \Rightarrow \text{PB}(pa)$ gives a relative high value

In fact, and most often, the mean values of the spatial measures exhibited in the extent of the study area can be considered as thresholds to determine the relative lowness and highness of the identified measures for deriving both legibility and permeability trends. In order to qualify the values that appear from the application of measures, fuzzy adverbs can be used to outline the different categories of values that appear.

3.6. City Permeability Computation and Interpretation

The parameters of permeability as introduced in Section 3.3 are further explored and associated to a series of geometric interpretations. Table 7 shows the computational expressions of the parameters given below:

- Small blocks: blocks can be visually perceived and extracted from an urban layout, and by making a difference between connected and isolated parcels. The concept of permeability is also related to the areas of the blocks identified (i.e., the smaller these areas the higher the permeability is likely to be).
- Segregated paths: segregated paths denote to which degree these paths are specific in the road network. However, such trends limit Path width (PW) and then reduce permeability.
- Hierarchical layouts: as already mentioned, hierarchical layouts are likely to generate cul-de-sacs and little route choices [10]. Indeed, the spatial structure that emerges from a streets layout affects the spatial configuration of blocks. Therefore, the shape of the blocks in a given layout can help to evaluate the local and global properties of an urban hierarchy. Figure 4a presents an urban layout whose network structure reveals a hierarchical pattern. In contrast, Figure 4b denotes a similar extent but the hierarchical pattern does not appear anymore. In fact, the paths that appear in the hierarchical network structure presented in Figure 4a are most often longer as compared to the non-hierarchical one illustrated by Figure 4b. It can be also observed that the hierarchical structure of a given layouts generates bigger blocks with notches in their contours (cf. Figure 4c). Blocks with relative low perimeter to area are likely to decrease this trend. (i.e., revealed by low values of the $PARA$ as mentioned in Table 3). It also appears that for a specified edge depth, the number of resulting cores (NCA) for blocks with many notches is higher than the one of the NCA for a block ones with fewer notches (cf. Figure 4c–f). Indeed the number of cores depends on the edge depth and should be preferably determined according to the mean size of the shapes that emerge from a given layout.



Figure 4. (a) Paths between two points a and b for (a) a hierarchical layout; (b) non-hierarchical layout; (c) a block in a hierarchical layout; (d) core areas of the same block; (e) same block when its notches are removed and has straight edges; and (f) the NCA of the block is reduced to one when all notches are removed.

Table 7. Parameters and rules that qualify the city permeability.

Parameters	Computational Rules
Small Blocks	An urban layout, has Small Blocks if \forall block $b \in \text{Environment} \Rightarrow \text{AREA}(b)$ gives most often a relative lower value
Segregated Paths	An urban layout, is less affected by Segregation if \forall path $Pa \in \text{Environment} \Rightarrow \text{WIDTH}(Pa)$ gives a relative high value
Hierarchical layouts	An urban layout is not Hierarchical if \forall block $b \in \text{Environment} \Rightarrow \text{PARA}(b)$ gives a relative low value $\wedge \text{NCA}(b)$ gives a relative low value

4. Implementation

The computational interpretations of legibility and permeability have been fully implemented on top of a spatial database and the identified urban components. Since both legibility and permeability are mainly perceived and studied along streets, the different parameters have been assigned at the street level. In other words, the different measures defined for parcels, blocks, edges or districts for all the components that are along a path are averaged and assigned to that path. For example, the average value of continuance for all the edges on both sides of a street are allocated to that street. This is done by a generation of buffer zones delimited by a distance higher than half of the streets' width around these streets, and then finding the edges that intersect such zones in order to compute the average continuance of each street. The streets' values are finally assigned to their vertices; this allows interpolating a raster map of the spatial distribution of these indices. In order to considering the border effects of study area, all the blocks and constituent parcels which are situated on the opposite edge of the border streets (Molavi Street, Shush Street, Vahdat Eslami Street and Rey Street) are considered too. Figures 5 and 6 present a series map results that exhibit the different parameter values computed for legibility and permeability. In the layers presented below, and for each raster map, pixel values are normalized by the unit interval and present low to high values via light to dark greys patches, respectively.

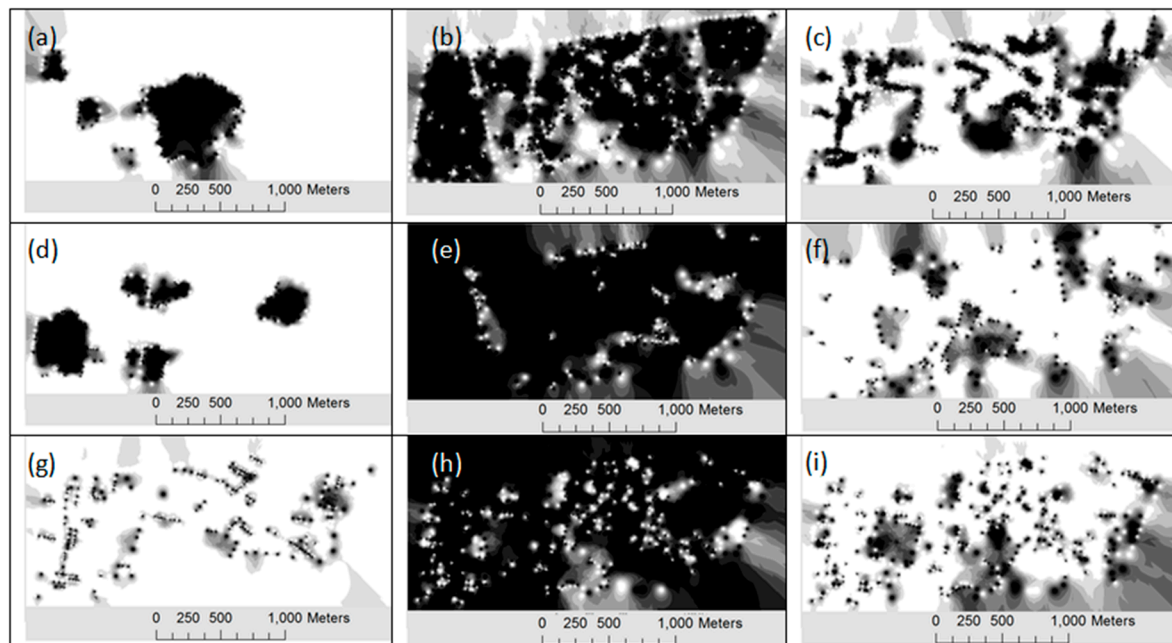


Figure 5. Parameters that denote legibility along the streets, that is, (a) singularity; (b) form simplicity; (c) continuity; (d) dominance; (e) clarity of joints; (f) directional differentiation; (g) visual scopes (determined by edges); (h) visual scopes (determined by paths); and (i) motion awareness.

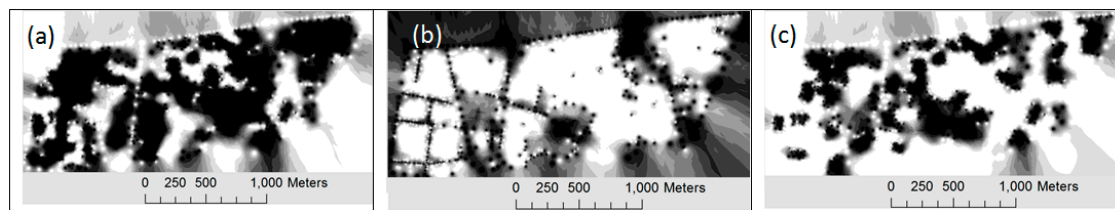


Figure 6. Parameters that contribute to permeability along the streets, that is, (a) small blocks; (b) segregated path; and (c) hierarchical layouts.

In order to favor a comprehensive and global evaluation, the different raster map layers illustrated by Figures 5 and 6 are spatially overlaid so as the values of the pixels in the different layers are averaged and assigned as a final value of legibility and permeability, respectively. Figure 7 presents the resulting raster map layers of legibility and permeability.

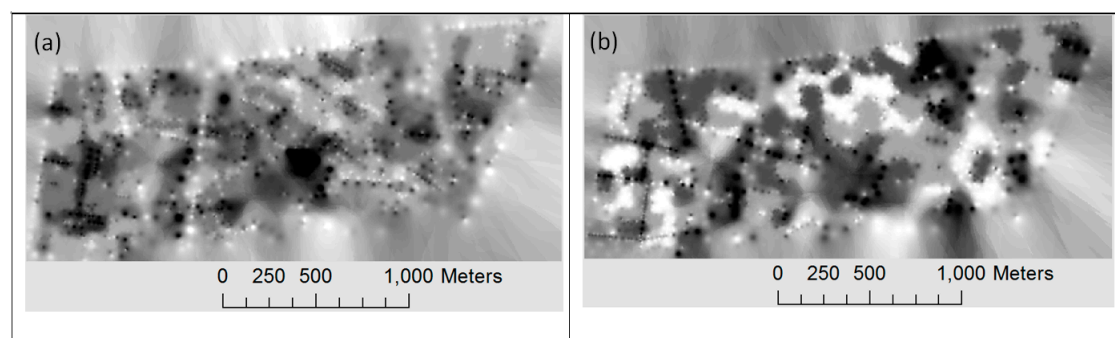


Figure 7. (a) Final legibility exhibited by an aggregation of the raster maps as shown in Figure 5; (b) final permeability generated by an aggregation of the raster maps as shown in Figure 6.

The second objective of our research is to confront the patterns that emerge to people's perceptions for the ones either familiar or unfamiliar with the selected environment. In order to take into account people's opinions regarding the legibility notion, the study area has been divided into nine main neighbourhoods whose centres are dotted from "a" to "i" in Figure 8. 29 critical points have been selected in the urban extent to study people's opinions regarding the concept of permeability (Figure 8).



Figure 8. Study area with numbered points presented to the panellists to assess permeability and legibility.

4.1. Experiment 1: Panel of Inhabitants

In the first experiment, a questionnaire complemented by instructions and definitions of the notions of legibility and permeability were distributed to a panel of 50 inhabitants who work, live or study in the selected area. The average age of the sample was 26 years with a sample deviation of 0.7. The panellists were familiar enough with the neighbourhoods and the selected points. A map of the studied area with the 9 neighbourhoods and 29 marked places accompanied by descriptions about their precise locations, and a table to fill the level of legibility and permeability, were given to the panellists (Appendix A). The questionnaires were answered by 50 panellists and the legibility and permeability notions have to be expressed in a range between 1 and 3 for high, moderate and less, respectively. The resulting opinions have been averaged in each neighbourhood and point and were used to derive a raster distribution of legibility and permeability for the extent as can be seen in Figure 9. The pixel values in Figure 9a,b are normalized by the unit interval, where darker pixels represent the more legible and permeable values, respectively.

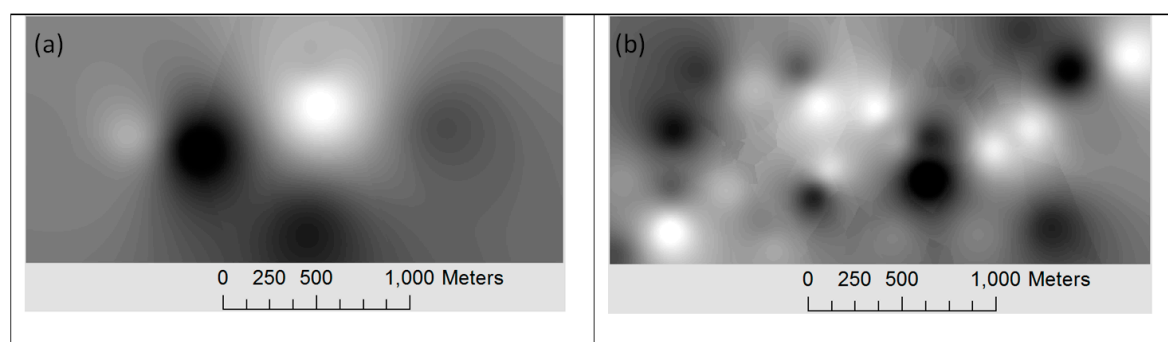


Figure 9. Raster layers from people's opinions in experiment 1 for (a) legibility; and (b) permeability.

4.2. Experiment 2: The Panel of Newcomers

Experiment 2 reflects the participants who have not seen the studied area before or only occasionally before the experiment. Fifty undergraduate students attending the University of Tehran compose the panel. The average age of the sample was 25 years with a sample deviation of 0.48. Before the experiment, all participants were introduced to the concepts of legibility and permeability as for the first experiment. At first they were presented a series of 270° panoramas showing urban scenes at the 29 points to assess their permeability (e.g., Figure 10). The idea behind is to take into account participants' opinions about the level of permeability, this being based on their own perceptions of the environment, as well as on their experienced mental maps [43].



Figure 10. Panorama taken at the intersection of Harandi Street and Shush Street (point No. 1).

Next, first via the maps given, participants were exposed to the limits of the extent and its main streets, and then were taken to the studied area. They strolled through the streets as pedestrians and observed and scrutinized all areas and the selected neighbourhoods to judge their legibility. They delineated their own sketches and took pictures from the critical landmarks and scenes in the neighbourhoods. They were left for one day to fill the questionnaires. Figure 11a,b present the raster

interpolation of the results. The pixel values are normalized between 0 and 1 and darker pixels represent the more legible and permeable values, respectively.

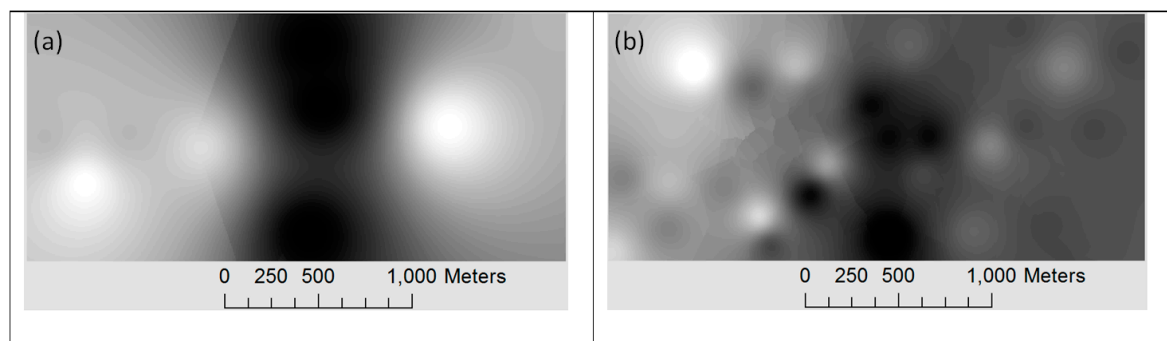


Figure 11. Raster layers that reflect people's opinions in experiment 2 for (a) legibility; and (b) permeability. Both experiments are summarized by the parameter values derived (Figures 5 and 6) and the final values of legibility and permeability (Figure 7).

5. Evaluation

In order to compare the resulting map layers to the computational findings, the raster maps exhibited by Figures 5–7 are differentiated by the raster layers derived from people's opinions as reflected in Figures 9 and 11. As done before, the raster maps were all normalized. Differences between the computationally generated maps and the ones derived from the two panels were summarized by a series of differential maps for both legibility and permeability parameters. Figure 12 outlines the main similarities (i.e., considered as similar for pixels with less than 10% difference). For example, the resulting graph presented by Figure 12a shows that 43% of pixels have a specific singularity and also high legibility as determined in or have improper singularity and also low legibility in experiment 1. The graph in Figure 12b reveals that opinions of both inhabitants and newcomers for a permeable environment are more compatible with the environments that have wider paths. Regarding legibility, inhabitants' opinions are much more compatible with the high continuance of an environment while newcomers' opinions are much more compatible with high dominance, clarity of joins and continuance of an environment.

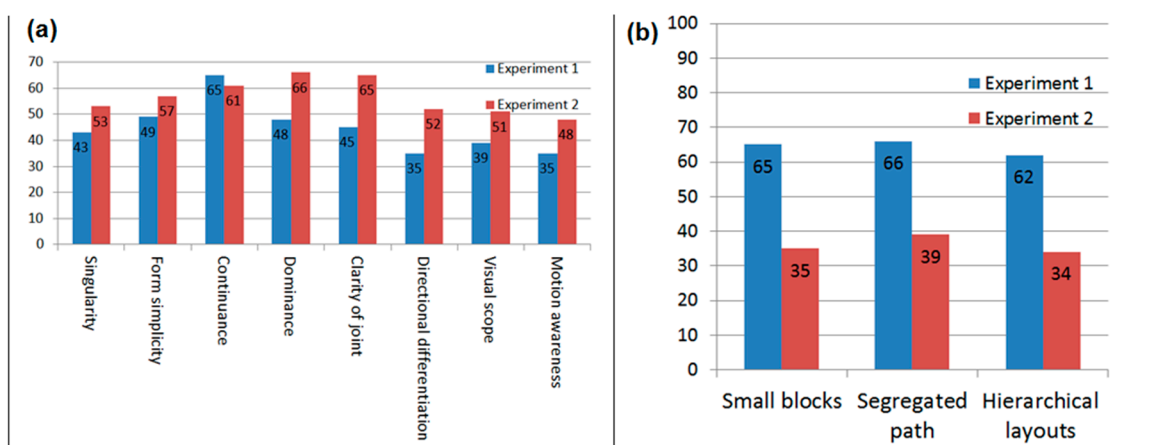


Figure 12. Experiments 1 and 2 outputs compared to the spatial analyses of parameters of (a) legibility; and (b) permeability (numbers refer to percentages of pixels with less than 10% difference).

Another important finding is that the results of experiment 1 match relatively well the permeability's parameters, while the results of experiment 2 match much more legibility's parameters.

Figure 13 shows that for example around 60% of the pixel values of legibility as outlined by experiment 2 match with less than 10% of maximum difference to the pixels as exhibited by the computational spatial analysis. On the other hand, this trend is satisfied for only 32% of the pixels in experiment 1. Regarding permeability, the result is slightly different since the experiment 1 is much more confirmed by the spatial analysis of permeability as compared to experiment 2.

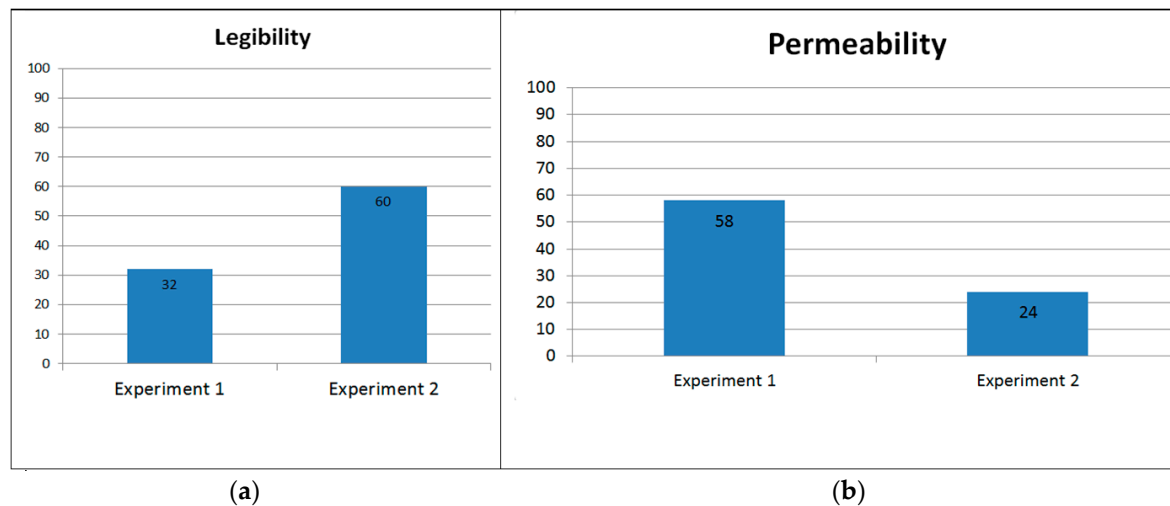


Figure 13. Experiments 1 and 2 outputs compared to spatial analyses of (a) legibility; and (b) permeability (numbers refer to percentages of street lengths).

Overall, the experiments show that inhabitants' perceptions of permeability are compatible to an extent of 58% to the spatial analysis of the urban layouts. This result is much significant than the 32% of compatibility between inhabitant's perception of legibility and the figures derived from the spatial analysis. On the other hand, the opinions of the second group of people unfamiliar with the environment show a 60% compatibility with the spatial analysis of legibility. This second group judged the permeability of a series of selected points by scenic panoramas from a pedestrian's point of view. Their judgment shows a 24% compatibility with the permeability determined by the spatial analysis.

The study of the notion of legibility as shown by Figure 13 also revealed that newcomers to an urban environment are likely to explore possible routes preferably based on the spatial and morphological characteristics (60% in Figure 13a). Regarding permeability, it can be observed that people, who are familiar enough with the area, generally know the streets, avenues, intersections and their spatial structures. Therefore, their opinions are more dependent to geometrical characteristics (58% in Figure 13b).

Overall the figures that emerge require further analysis. An important one is to consider additional semantics associated to the urban layout and urban scenes that have significant impacts on urban navigation. For instance, architectural differences, parcel landuses, path categories should be taken into account and qualified to a certain degree as those should have an impact on several measures introduced in this paper (for example singularities and symmetries are amongst the many qualities that are likely to be impacted). Additional experiments on larger and different urban environments should be also conducted and are currently planned as further experimental works.

6. Conclusions

The research presented in this paper develops a modelling approach and computational framework to study the concepts of permeability and legibility of an urban layout. These notions are considered as two important properties when evaluating the structure of an urban layout as well as navigation capabilities in the city. The novelty of the approach is that the computational framework is formally developed, and built on the notions of legibility and permeability as introduced by Lynch and

Bentley, respectively. Another peculiarity of our research is that all the parameters identified have been successfully implemented in a GIS software and spatial database. The metrics used to characterize legibility and permeability have been mainly derived from a series of geometric properties also applied elsewhere in landscape ecology primarily, and applied to the main parcels that appear in an urban layout. These measures are complemented by another series of metrics that characterize the spatial configuration of the paths and edges in the urban layouts.

The legibility and permeability have been computationally defined and implemented in a neighbourhood of the city of Tehran. The results of the computational experiments are compared to people's opinions, either inhabitants that are familiar with the environment or newcomers to the environment via two independent experiments.

The experiment findings reveal different degrees of matching between the computational analysis of an urban layout and how legibility and permeability is perceived by people's opinions depending on their initial knowledge of the considered urban layout. In particular, the detailed results show that newcomers to an urban place are likely to perceive the sense of legibility based on spatial and morphological characteristics rather than inhabitants. As for the permeability of urban environments, people who are familiar enough with the environment have overall recognized the permeability of environment with a close dependency to spatial structural properties.

Furthermore, this research shows that a spatial structural analysis of an urban layout might have an interest for urban navigation. As stated by [18] 'The city is the creation of economic and social processes that operate within an envelope of geometric possibility defined by human minds'. Indeed, our experiments might contribute to show how structural properties play a role in the comprehension of an urban layout, as well as it also provides a framework for further analysis of navigation opportunities in the city. In order to refine the way legibility and permeability are derived, future research might for instance assign different weights, for example using regression techniques, to the factors identified in order to reflect the relative importance of the different structural trends identified. Last but not least we also plan to study how legibility and permeability might be closely related and/or interdependent.

Author Contributions: The corresponding author, Tolue Silavi, developed the methodological framework as well as the computational implementation and is the main writer of the paper; Farshad Hakimpour and Christophe Claramunt were acting as supervisors and provided feedbacks on the design and on the writings; Farshad Nourian contributed to urban design analysis, data analysis and gave suggestion during the manuscript revision.

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Appendix A. Questionnaire Given to the Panellists

Permeability

This questionnaire is designed to explore the permeability of a neighbourhood, located in the central part of Tehran which is well known as it is a crowded area of Tehran's bazaar. As you can see from the map in first page the neighbourhood is surrounded by Vahdat Eslami, Molavi, Shoush and Rey streets.

The Permeability in each point and its surrounding environment can be defined as:

- The ability to sense or move through a given environment.
- How far and how easily one can sense or move through an environment.
- How the physical properties of environments mitigate either perceptual or locomotive permeability.

There are 29 critical points on the map of study area to give your opinions on the concept of permeability. Please fill the table for each point with one of the low, moderate or high degree of permeability.

No.	The Title of Point	The Degree of Permeability		
		High	Moderate	Low
1	Shush Street-Harandi Square			
2	Shush Street-Khayyam Intersection			
3	Shush Street-Shahid Borbor Intersection			
4	Shush Square			
5	Rey Street-Shush Park (Anbar Gandom)			
6	Rey Street-Shahid Shams Intersection			
7	Molavi Crossroads (Molavi Street-Aminolsoltan Intersection)			
8	Molavi Street-Zokaei intersection			
9	Molavi Street-Mohammadiyeh Square			
10	Molavi Street-Takhti Square			
11	Vahdat Eslami Street-Mokhtari Intersection			
12	Vahdat Eslami Street-Shoush Intersection			
13	Takhti Street-Mokhtari Intersection			
14	Fallah nafari street-Abdolkhoseini Intersection			
15	Ba Afafe Pour Street (between Vahdat Eslami and Takhti)			
16	Mokhtari Street-Yahyavi Intersection			
17	Ghaem Street (between Khayam and Takhti)			
18	Harandi Street-Zali Ghomi Intersection			
19	Maleki Street-Shahid Haqqani Park			
20	Almasian Street (Khorsand)			
21	Azimi Street-Moghaddasi Intersection (Saboon paz khane)			
22	Nasiri Street-Marookhane Intersection			
23	Borbor Street-Jazmani Intersection			
24	Ardestani Street-Pirmoradi Intersection			
25	Hatami Brothers Street-Abbas Azadi Intersection			
26	Shush Park-Aminolsoltan Street			
27	Khayyam Street-Bagh Angoori Intersection			
28	Khajooye Kermani Park-Moradi Street			
29	Hamdollahi Street-Khosrojerdi Intersection			

Legibility

This questionnaire is designed to explore the legibility of a neighbourhood, located in the central part of Tehran which is well known as it is a crowded area of Tehran's bazaar. As you can see from the map in first page the neighborhood is surrounded by Vahdat Eslami, Molavi, Shoush and Rey streets.

The legibility of each environment can be defined as:

- The ease with which people understand the layout of a place.
- The capacity of a space to give clues to the understanding of the system as a whole.
- The capacity of a space to facilitate one's orientation in a city.

There are 9 sub neighbourhoods on the map of study area to give your opinions on the concept of legibility. Please fill the table for each neighbourhood with one of the low, moderate or high degree of legibility.

No.	The Extent of Neighborhood	The Degree of Legibility		
		High	Moderate	Low
1	Vahdat Eslami Street-Below the Molavi Street and above the Shoush Street			
2	Takhti Street- Below the Molavi Street and above the Shoush Street			
3	Mokhtari Street- Between Takhti and Vahdat Eslami Streets			
4	Khayyam Street- Above the Shush Street			
5	Molavi Street- Between Saboon Paz Khoone and Haj Gholamali Bazaar			
6	Shush Street- Between Shush Square and Khayyam Street			
7	Saheb Jame Street- Near Shush Park			
8	Rey Street- Around Molavi street			
9	Molavi Street- Between Mohammadiyeh Square and Molavi Crossroads			

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