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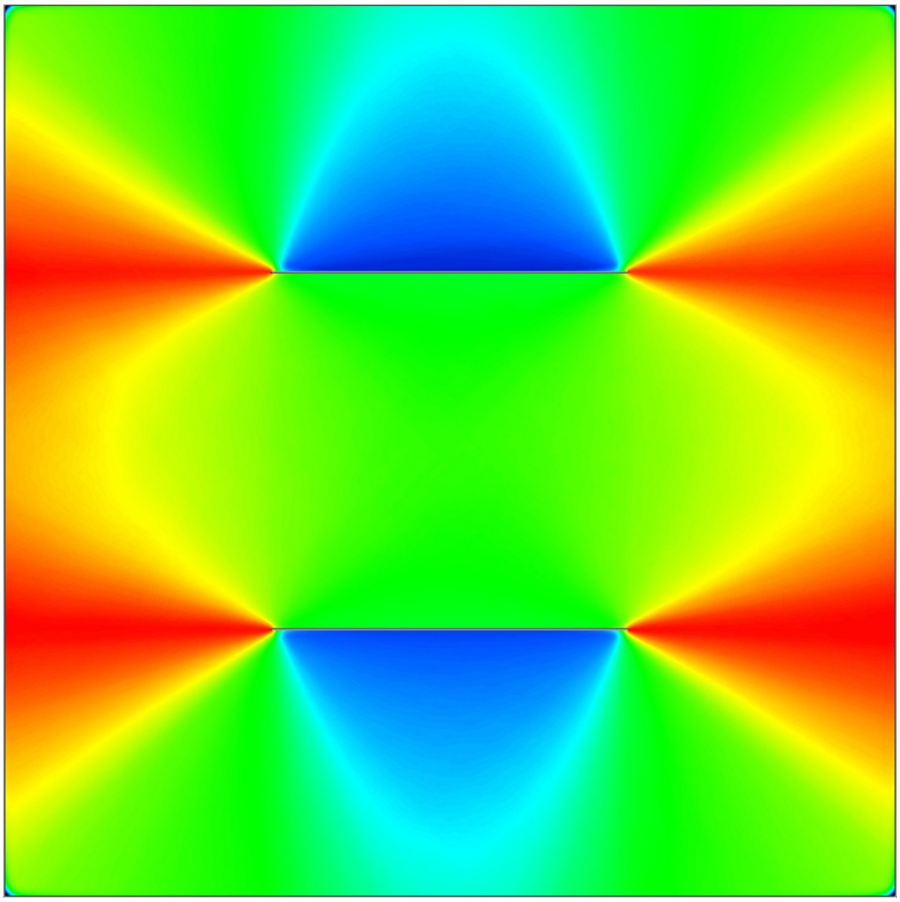

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This paper concerns the development of a new computational stochastic analysis in order to gain insight into situated vision in spatial environments. It is structured in three parts. The first two parts present the theoretical framework for the new model, based on the following propositions: firstly, that isovists are bound configurations containing one or more areas of spatial points that are intervisible; secondly, that observers are capable of *embodied projection* in space, anticipating how relations seen from a position can be seen from other regions that are one step away from the current position, and building expectations about other spaces visible from these regions; and thirdly, that we need a method that describes isovists not as static units but as dynamic seeds for a global framework of knowledge. The final part of the paper presents the new method with the following functionalities: a. continuous-time stochastic discretisation of space for isovist root selection and isovist generation; b. quantification of geometric isovists properties based on successive isovist intersection; c. high resolution of isovist analysis; d. four quantitative isovist measures. These measures are discussed in hypothetical layouts and in the context of Mies van der Rohe's Farnsworth House. The paper contributes a dynamic modelling technique to the discussion of diagrams and their capacity to represent embodied vision as actualised and virtually embedded possibilities, rather than as static structures.

Keywords:
Isovist, stochastic, overlap, inference, embodied projection.

1. Introduction

Analytical models and diagrams[1] used in space syntax research describe the structure of spatial organisation, and index relationships of visibility and permeability in two dimensions. As such, they explain and represent spatial characteristics across the entire domain of a space. A whole sedimented 'history' of moving and cognising in layouts is 'externalised' in this way within the space syntax diagrams and models. Research has often focused on the link between embodied vision and the structure captured in the diagram, between the internal, partial and temporary states of the former and the externalised system of relationships represented by the latter. The connection between these two 'states' is expressed as the relationship between local spatial characteristics and global scale relations. The correlation of connectivity (local measure) to integration (global measure) is used to account for the ways in which what can be seen from local parts is a good guide for all-to-all spatial interconnections (Hillier, 1996). Described as intelligibility, this measure captures a key formal property of spatial complexes, and a generic function of layouts (*ibid.*). Intelligibility is a mathematical expression of the capacity of a spatial complex to provide an intelligible picture without conscious effort (*ibid.*), and has implications for ease of movement and navigation (Penn, 2001; 2003).

Notes:

[1] We regard visual analytical outputs produced by space syntax analysis as diagrams in their function to represent the distribution of spatial properties through colour, aiding an intuitive understanding of spatial layouts rather than a literal numerical understanding of distribution of values.

A second strand of research approaches the relationship between local and global characteristics from the viewpoint of immersed vision and the human subject. Conroy Dalton conducted experiments through virtual environments, which explored route selection as a relationship between simplest angular route and maintenance of close heading towards a destination (Conroy Dalton, 2001). Similar kinds of experiments by Hölscher and Brösamle (2007) in real environments have tested how familiarity with spatial complexes affects movement. Findings by the latter authors suggest that movement choices by users who do not have previous knowledge of a layout rely on connectivity, as opposed to choices by people who have such knowledge and use integration[2].

Both mathematical expressions of intelligibility and empirical studies of spatial cognition have offered significant measures and concepts. However, the question of the cognitive relationship between locally observed relationships and global structure through embodied vision still remains open. Space syntax cannot yet capture how spatial knowledge obtained through embodied vision contributes to and affects global scale spatial understanding. We argue that this deficit is due to the lack of models and diagrams capable of measuring and visualising characteristics of temporal spatial practice. We also suggest that this shortage derives from the way in which spatial information and cognition are conceptualised. Using diametrically opposite frameworks of local and global relationships, and bipolar notions such as perception and cognition leads to static models and structures. One such example is the division between the isovist – the 'set of all points visible from a given vantage point in space' (Benedikt, 1979, p.47) – and Visibility Graph Analysis (VGA) (Turner et al., 2001). The former is generally interpreted as an itemised geometrical unit of information, and set apart from the latter, which is a graph-based structure. Turner has argued that spatial perception should be examined 'as an active or dynamic process occurring between the agent and the environment' (Turner, 2003, p.658). Yet, spatial description still lacks methods that can describe the mutual relation between observers and the spaces they observe, akin to Gibson's definition of the ecological link between occupant and the environment (Gibson, 1979).

In this paper we present a new method and tools based on a continuous-time stochastic generation of isovists, measures and mappings. The larger questions we raise through this work are: do graph-based measures of visibility relations sufficiently account for spatial cognition? Can we, additionally to VGA, provide probabilistic methods so as to link spatio-temporal dynamics with synchronic frameworks of understanding? We suggest that in order to be able to address these questions, we need to go beyond static approaches to computation and visualisation.

The paper is structured in three parts. The first part reassesses isovists, suggesting that their definition either as geometric units or as a relational set of points with reference to the point of observation underemphasises their property to include one or more areas of mutually intervisible locations, a characteristic captured by Turner et al.'s 'clustering coefficient' according to visibility distance (Turner et al., 2001). We explain that isovists are geometrically bound network-like structures. The way in which these characteristics relate to embodied vision and human intuition is through *projection* of the body to regions within the isovist. Such projection facilitates consideration of how the presently occupied vantage position appears from these other regions. It also enables the construction of expectations of what further spaces may become visible spaces from these regions.

The second part of the paper presents a new method for isovist analysis based on the stochastic construction and successive overlaps of isovists.

Notes:

[2] A number of additional studies, such as those conducted by Wiener and Franz (2005) have suggested that isovist quantitative data predict behaviours within an environment.

The proposed model has four key novel functionalities: a stochastic approach to isovist root selection and analytic discretisation of space; continuous-time calculation of geometric isovists with a 360-degree field of vision; high resolution spatial mappings, and four quantitative isovist measures. These measures are illustrated and discussed via eight hypothetical layouts testing the impact of inserting a solid block and a set of partitions inside a space. The final part of the paper provides application of the tool to Mies van der Rohe's Farnsworth House. The purpose is mainly to test the methodology in the context of hypothetical and real examples rather than provide a coherent interpretation of spatial cognition or principles of spatial composition in this house. The aim is also to add to the lineage of tests that have been produced by Peponis, Turner and their colleagues on this building, and thus, provide a basis for comparison with previous work.

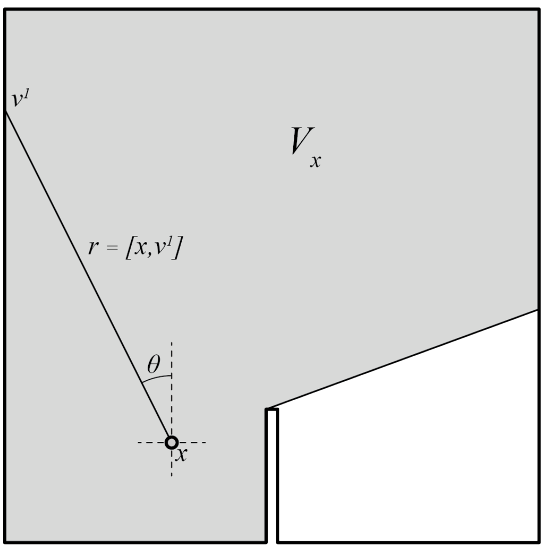


Figure 1:

The isovist described via radials.

(From Benedikt, 1979)

The major proposition in this paper is that stochastic isovist generation, and measures based on isovist intersection can function as seeds for a new kind of analysis. Such a methodology has the potential to address relationships between embodied vision and the overall structure of spatial environments. This remains at the level of hypothesis and subject to future analysis.

2. Geometric isovist fields and visibility graphs – similarities and differences

We begin by re-examining isovists and VGA so as to outline the differences between the two methods and their limitations. Benedikt's definition of the isovist as a system of points visible from a vantage location (Benedikt, 1979) and the measures used to describe it (isovist area, real surface perimeter, occlusivity, radial variance, radial skewness and circularity) imply that an isovist is a relational set as well as a geometrical unit (Figure 1). However, the quantitative isovist fields he proposed via contours discretise space through isovist vantage points, each of which represent their respective isovist measures. As a result, the relational sets of all points contained in isovists are replaced by points of observation.

The work of Turner et al. (2001), upon which VGA and the DepthMap software is based, also discretises a layout, superimposing a parametrically defined tessellation on a plan. Points at the centre of each cell are taken as the roots of analysis, removing any potential bias related to isovist root selection. In VGA these points are stored as vertices constructing a graph of edges that represents their binary inter-connections (*ibid.*). This approach is fundamentally different to isovist fields as geometric information is explicitly discarded (*ibid.*). From this graph, DepthMap can produce standard space syntax measures, such as neighbourhood size (or connectivity) and integration (Turner and Penn, 1999). DepthMap offers analysis of isovist geometric properties[3], but there is a clear analytical split between isovist analysis and visibility analysis, with the former capturing characteristics of isovist geometry and the latter graph relations. This split is present within the two separate strands of analysis in the programme; one for isovist calculation and another for visibility graph. A correspondence between connectivity and Benedikt's isovist area exists, but there is no similar relationship between graph properties and isovist geometry in relation to other measures. This is because the geometry of vision is embedded in the local-scale relations of connectivity, but discarded in the calculation of clustering coefficient and integration. Local measures preserve geometric isovist information, as opposed to global ones which discard geometry for all-to-all graph relationships. The former are associated with what we observe from local parts; the latter are related to what we can process and understand as conceptual structure.

An isovist does, however, contain points which have a relation both to the point of observation and to other points that are internal and external to its neighbourhood. Turner et al. (2001) use this idea to explain the generation of the visibility graph through 'first-order' and 'second-order' relations. The former refer to two isovists that overlap in a way that their generating roots are mutually visible (Figure 2a). The latter concerns relations among locations that are connected through a third point situated in the common area of the overlap (Figure 2b). The relations of spatial points inside an isovist and outside of it are embedded in the measure of 'clustering coefficient', defined in graph terms as 'the number of edges between all the vertices in the neighbourhood of a generating vertex divided by the total number of possible connections with that neighbourhood size' (Figure 2c; *ibid.*, p.109). For Turner et al., the clustering coefficient measure expresses the potential for 'visual looping'. In the Farnsworth House it is interpreted as explaining the distinction between architecture as disposition of objects and as spatial configuration (*ibid.*). This measure also relates to decision-making and navigation, including how much of the observers' visual field is retained or lost as they move in a layout (*ibid.*).

The measure of clustering coefficient has similarities with overlapping spaces proposed by Psarra

Notes:

[3] *These are: connectivity, isovist area, compactness, drift angle, drift magnitude, maximum radial, occlusivity, and perimeter.*

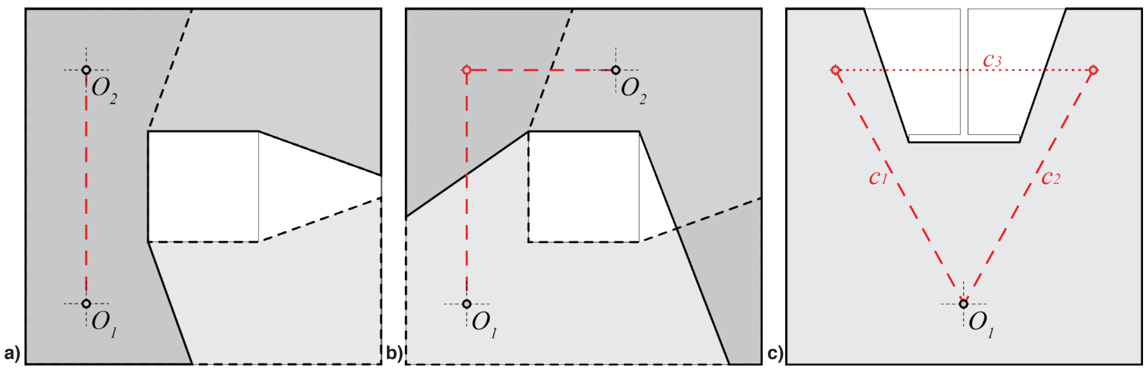


Figure 2:

a) *First order connectivity between isovists.*

b) *Second order connectivity between isovists.*

c) *Calculation of clustering coefficient. Total actual edges between nodes (c_1+c_2) is compared to all possible edges ($c_1+c_2+c_3$).*

(From Turner et al., 2001)

(1997a; 1997), and s- and e-partitions proposed by Peponis et al. (1997); that is, 'informationally stable' spatial units, derived from discontinuities of shape that affect visibility (*ibid*.). These partitions describe thresholds of informational stability that are geometrically defined. However, as Turner et al. suggest, isovists are good intuitive tools for thinking about space. As opposed to e-partitions and s-partitions, which are generated by built shape, isovists derive from space as it may be seen and retain the geometry of vision at each spatial point. Yet, when isovist structures are graphed, their shape, directionality, geometry and the gradual overlaps of isovists are exchanged for formless graph relations. In an environment we perceive not only interconnections of spatial positions, but also 'regions' of positions clustered and bound by shape and geometry. Despite Turner et al. acknowledging the relational logic of isovists, operationally and conceptually, we are faced with a divide between isovists and graphs[4]. The implication is that the former are discrete geometrical elements as opposed to the latter, which are relational and free of shape or geometry.

2.1. Redefining the isovist – Isovist neighbourhood relations

Our *first proposition* is that isovists have the capacity to be both geometric expressions of situated vision and network-like structures. We explain this proposition starting with Benedikt's original definition (1979). An isovist consists of:

i. A viewpoint, or origin vertex [O]

ii. A set of points with direct visual connection to the origin [S]

iii. A geometric perimeter enclosing 'S' [P]

Within a convex isovist all points of 'S' have centralised and symmetrical relations with respect to 'O' (Figure 3a). As isovist convexity reduces, 'S' divides into subsets (Figures 3b, c). In this case relations inside the isovist can be described as follows: firstly, any pair of points within each subset (S1, S2, S3,…) are mutually visible and have distributed relations to each other; and secondly, points in each subset are connected to points in other subsets only indirectly via 'O', which means they are in a symmetrical and non-distributed relationship to

Notes:

[4] *It is essential to stress that the authors do not regard the isovist as a discrete unit; it is only the way in which VGA and various applications of isovist analysis treat isovists as singular entities that we are concerned with here.*

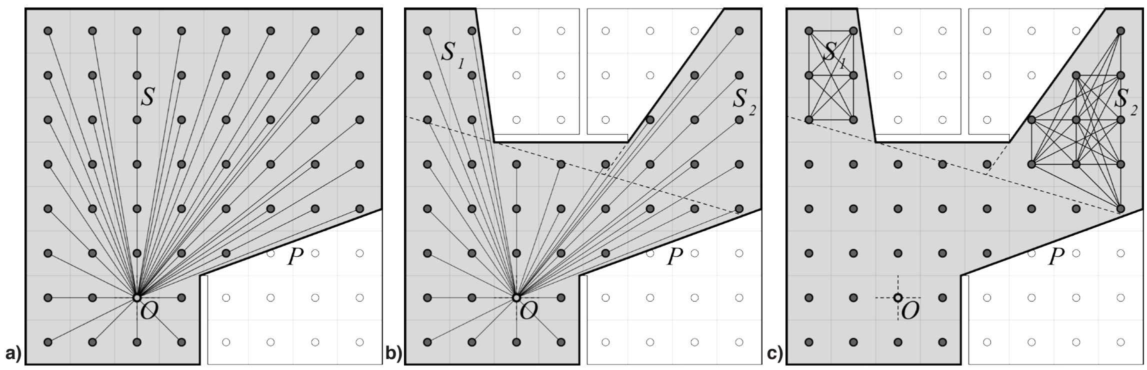


Figure 3:

a) *Isovist expressed as origin, set of points and perimeter.*

b) *Isovist with increasing occlusive nature develops sub-sets S_1 and S_2.*

c) *Sub-sets S_1 and S_2 as distributed network regions with second order connectivity via O.*

each other with respect to 'O'. More specifically, the points within each subset are intervisible, while those across subsets are co-visible from 'O'. These complex relations extend isovists beyond discrete units and even beyond connectivity or neighbourhood size[5], as the set of vertices immediately connected through an edge (Turner et al., 2001). They bring us to a re-formulation of the isovist definition from *a bounded set of points all visible to a vantage point*, to *a bounded set that has the above property* but *also includes one or more regions of points that are intervisible*.

The implication is that an observer at a vantage location grasps a relational set of points as a bound configuration, in Hillier's notion of the term[6] (1996). Taking isovist area as an example, viewers standing at 'O' are likely to perceive a location 'L' within the distributed network of 'S_2' (Figure 3c) simultaneously with the isovist area in which they are located. Observers can hypothetically project their body to another location within the isovist with respect to 'O'. This inherently includes knowledge of 'O' and inference of how the 'O'- to -'L' relationship will look form 'L'. Tied to situated vision, this interpretation takes us to a *second proposition: isovists are geometrically bound configurations consisting of a vantage point and hypothetical alternative viewpoints*. Through the relational logic of isovists, observers construct expectations of how the dynamics of spatial connections may alter from other regions, and speculate as to what might be revealed with movement. This hypothetical extension of the body to other regions implies that embodied vision is dynamic even when a viewer is stationary. Even at the level of a single isovist, spatial cognition depends on a complex network of spatial relations among actually and virtually occupied positions.

A similar proposition is put forward by Koch (2012) in a discussion of retail space, where using an argument by Osborne (2008), he suggests that mannequins exemplify a 'potentially imagined elsewhere' based on the expression of identity and 'encouraging cognitive relocation and identification with an inanimate body' (Koch, p.10-11). We suggest that cognitive relocation can be triggered by inanimate bodies or objects, but belongs to more general processes of *embodied projection* we consciously or unconsciously perform in spaces[7]. These exist independently of specific building types, and over and above the issue of identity. Koch introduces this idea starting from the need to invert a common assumption in certain space syntax studies that identifies the isovist with the 'subject' and the spatial surrounds with the 'object'. He points out that a certain kind of 'de-subjectification through deployment of multiple isovists in an equidistant grid', occurs in Turner's VGA (2012). We wish to avoid the duality between local and global, subject and object in favour of a process-based relationship between people and the environment, and process-based spatial understanding. The larger theoretical implication of this duality is that isovists are elements, entities or discrete units of information while graphs are about relationships. Any consideration that treats these representations as itemised should consider two facts: first, they are all defined as sets of points and distinguished from other points in a spatial continuum according to principles of linearity, convexity or isovist polygon formation; second, they are purposefully *selected* as representations for graph-based analysis in space syntax so as to overcome the indivisibility of space into discrete elements. They might be represented as nodes in a graph, but in geometrical and spatial terms are neither entities nor elements, but relational frameworks.

2.2. Overlapping isovists

In order to expand the relational logic of isovists into an analytical framework we consider isovists from two successive points along a path (Figure 4). Points O_1 and O_2 are invisible from each other,

Notes:

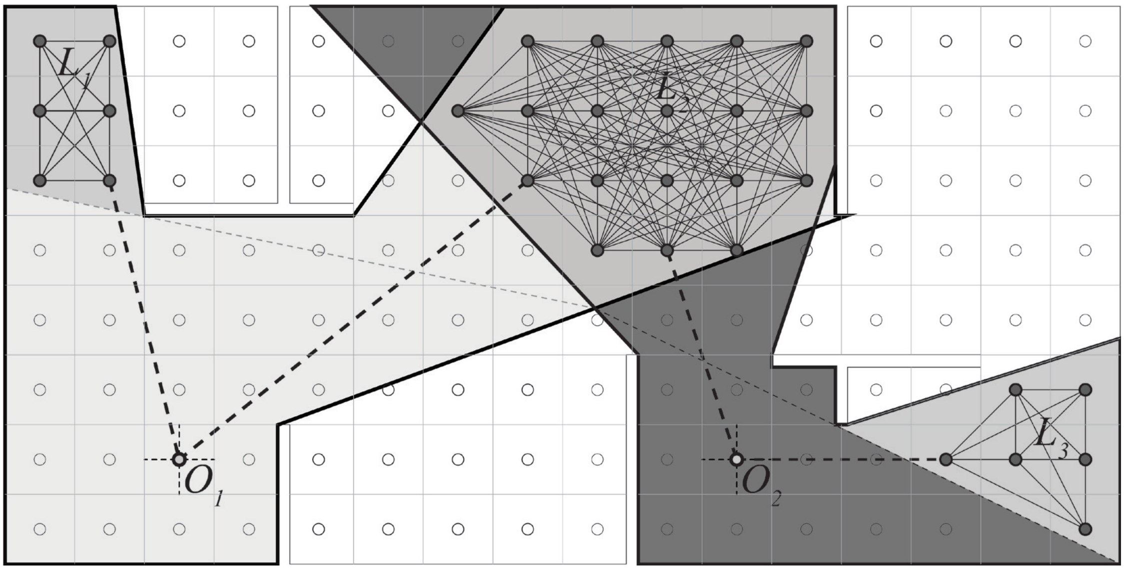
[5] *Turner et al. (2001) explain that neighbourhood size can be thought of as equivalent to the isovist itself.*

[6] *Configuration is defined by Hillier (1996) as 'relations taking into account other relations' (p.1).*

[7] *Or even, as Psarra (2013) and Koch (2013) explain, in embodied and disembodied explorations through the imagination.*

Figure 4:

Overlapping sequential isovists and their discrete sub-set regions.



Notes:

[8] *More particularly, the value recorded is the sum of the values of all isovists each spatial point belongs to the value of the isovist generated from each point (as the root location).*

yet their regions share a region of overlap (L_2) and contain regions of distributed networks (L_1 and L_2). One visual step separates L_1 from L_2, L_2 from L_3, and O_1 from O_2. During each of these steps, one region or point moves out of view and a new one becomes visible. In Turner et al.'s terms, there is first order visibility from L_1 to O_1, O_1 to L_2, L_2 to $O_{2,}$ and finally O_2 to L_3, and second order relationships from L_1 to L_2, O_1 to O_2, and L_2 to L_3. In short, the isovists from O_1 and O_2 can be related to one another via their overlap region. This relationship can be numerically expressed by assigning an average value (such as geometrical area) from the isovists constructed at O_1 and O_2 to all points in L_2. This value captures the combined values of both isovists. If applied to all spatial points in the configuration it describes the extent to which each point is *one visual step away* from large or small isovist areas.

Points O_1 and O_2 are considered as lying on a notional path, but all pairs of locations with a one-step or a two-step visual connection to each other generate isovists that overlap and contain these locations (Figures 5a-c). Points that contribute a value to any distinct third point might either be intervisible (first order) or co-visible from the third point, which means hidden from each other by an occluded edge (second order). It is therefore possible by compiling all values for all isovists a point falls within, and for all points in space, to produce quantitative visual fields. The spatial locations generating such fields do not record the values of isovists at isovists origins, but the values of all isovists to which each of these locations belong[8]. A value at any location provides a measure of the extent to which when taking a step away from this location in all available directions, or just around the corner from where an observer stands, the field expands or contracts (if the measure in question concerns area), is convex or star-like (if it concerns compactness), and so on.

It may at first seem counter-intuitive to record isovist values to all points in an isovist, rather than at the vantage point. However, as movement through space consists of continuous visual transformation, discrete vantage points do not usually correspond to any state of vision through motion. In terms of spatial cognition, the importance of overlap is that

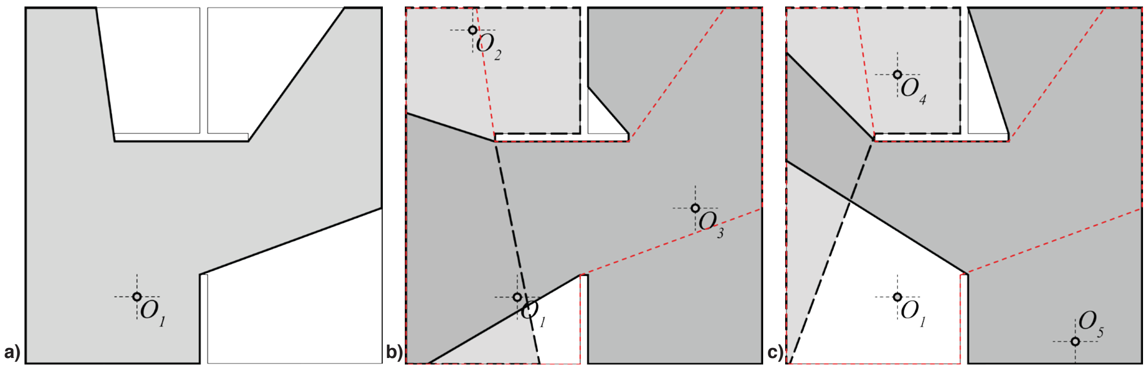


Figure 5:

a) *Isovist O_1 in space defines a visual threshold of a single visual step.*

b) *Isovists O_2 and O_3 occur within this threshold and so overlap point O_1, therefore passing value to it.*

c) *Isovists O_4 and O_5 occur beyond this threshold and do not overlap point O_1 or pass value to it.*

it captures characteristics that are directly visible and additional ones that are not evident but can be inferred from a position. The projection of the body from actually to virtually occupied regions previously described concerns not only the relationship of O_1 to L_2, or to the rest of the points visible in the neighbourhood of the isovist, but also relations which cannot be seen from O_1 but can be anticipated as a possibility (Figure 4). The anticipation of the potential presence of O_2 is provided from O_1 by seeing L_2 and the occluded edge from O_1. From O_1, L_2 is understood as belonging to an area of overlap constructed by the isovist of O_1 and another space. Moving from O_1 to L_2, what is inferred as possible is translated to actual as relationships are seen and stored in memory.

Modelling properties that occur one step away or just around the corner can therefore capture the probabilistic potential of movement. What we mean by 'movement' does not concern a continuous path through a series of spaces[9], or large-scale exploration covering the entire layout or empirically observed aggregate movement of people. It rather describes '*one step of actual or hypothetical movement' falling within an isovist neighbourhood from any location and in any direction*. Depending on the shape and configuration of a layout, this 'step' can be relatively short or long, confined to local scale or extending to the global scale of the layout. In the case of a long 'step', as in a classical enfilade sequence, the axial symmetry of thresholds, occluded radials, and the alignment of overlapping regions induce observers to anticipate a sequence of rooms lying ahead, not yet seen but inferred from a distance. Embodied projection formed at the first point of inference is re-evaluated and if necessary adjusted at the second point and in subsequent points. At the opposite end of this example is a jagged sequence of openings, where thresholds and isovist overlaps alternate on either side of the layout. The longest 'step' in this case is persistently one or two rooms long, with embodied projection and inference confined to a small scale.

In modelling situated vision as process we cannot rely on the interaction of what we see directly with all-to-all relationships, simply because the latter is measured outside direct experience (particularly for first-time viewers). We propose that it is the transformation in visual fields expressed as the relationship between each spatial location and the points that are immediately accessible from it (or that lie just around the corner), that capture the probabilistic potential of movement and the continuity of vision.

Notes:

[9] *Certain studies have examined movement along hypothetical paths created by point isovists (Psarra and Grajewski, 2000; Conroy Dalton and Dalton, 2001; Tzortzi, 2007; Psarra, 2009; Tzortzi, 2009, 2011) and have observed how visual relations and quantitative measures change or remain constant along those. Although isovists were drawn along a sequence, at any given point the representation consists of static isovists. Even when isovists are overlapped, as with Hanson (1998), Psarra and Grajewski (2000) and Tzortzi's work (2007; 2009; 2011), isovists are achieved either from individual points that are architecturally significant or at regular intervals, and are drawn in isolation.*

3. A stochastic system

In this section we present a prototype model for stochastic generation and visualisation based on isovist overlaps. We generate isovists within an imported architectural plan using a method akin to Benedikt's optical array or radials (1979). Radial lines are arrayed at 1.5-degree increments to give a 360-degree field of vision. Isovist polygon vertices are defined at each nearest plan-line to radial intersection[10]. The process takes less than one tenth of a second per isovist in a typical plan and has four key features:

a. Stochastic sampling of root selection of isovists

Space is ultimately not discrete but indivisible, consisting of an infinitesimal number of points. When constructing isovist fields in a plan from 'all points' (rather than isovists in individual locations of special interest), one issue requiring resolution by an appropriate convention is the identification of 'all points' from which isovists will be drawn. As previously discussed, DepthMap establishes sample points by superimposing a lattice on a plan, and defining points at the centres of the square tiles of the tessellation (Turner et al., 2001). The chosen grid resolution is either relative to the scale of the plan, or chosen so as to capture meaningful features or a 'human-scale' grid spacing of around one metre[11] (*ibid.*, p.106). The outcome is a 'near-full' description of a space according to criteria established by scale and/or human occupation by the software user. We propose an alternative stochastic method for discretising a layout through a continuous random selection of *x*, *y* coordinates that identifies isovist root locations. This rapidly provides a probabilistic and even distribution of sample points throughout a plan (Figures 6a, b).

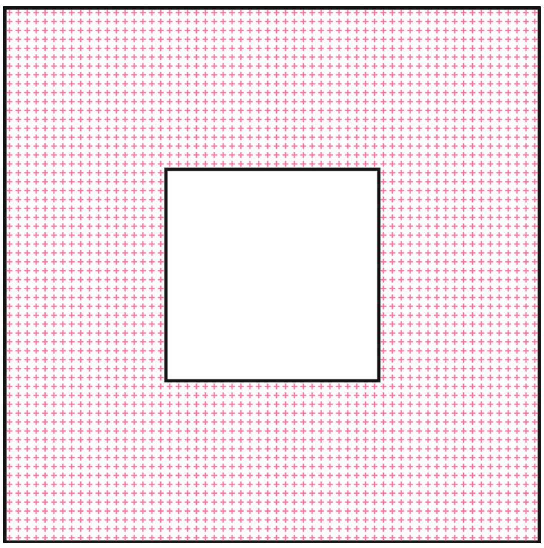
b. Continuous-time generation of isovists and isovist intersections

Isovist geometric values are calculated from the sample points and successively recorded to all points they contain. The sequential overlap of isovists generated in this manner provides a spectrum mapping. It is essential to explain that although equivalent results can be obtained by overlaying a tessellation and calculating geometric values of isovist overlaps, the stochastic approach

Notes:

[10] *The model provides isovists according to different classifications of space, ranging from spaces that are both visible and accessible to those that are seen but cannot be accessed as they are behind glass, or are not occupiable being situated inside a gap on the floor or a void (Figure 22a, see in Endnotes). Two additional categorisations can account for spaces seen through reflective materials, allowing the model to capture certain particularities in space design and materials (Figures 22b and c, see in Endnotes). These will be discussed in detail in future work.*

[11] *In DepthMap, however, there is automatic choice of the grid size based on the maximum dimension of the input drawing and which is not related to human scale. This can be altered by the software user.*



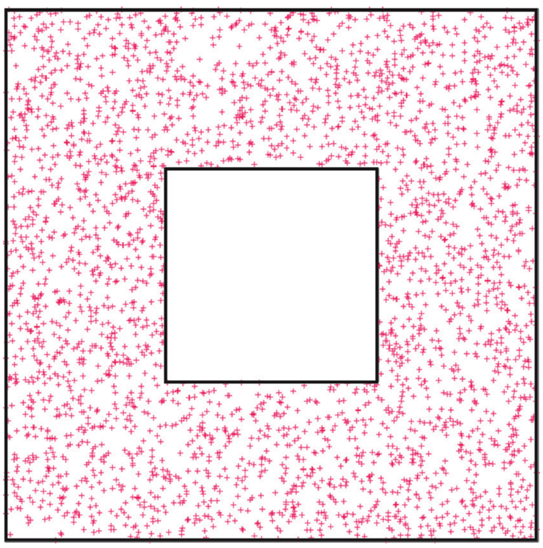


Figure 6:

a) *An orthogonal grid centre tessellation of 3,000 points across a hypothetical layout.*

b) *A comparative stochastic distribution of 3,000 points across a hypothetical layout.*

to sampling points and the continuous analysis it facilitates has three advantages. Firstly, stochastic sampling continuously and randomly selects spatial points resulting in even levels of discretisation. It thus circumnavigates the problem of how to define the parametric 'scale' of the superimposed grid for each plan and comparatively across different plans. Secondly, the method is a continuous-time stochastic process, which allows continuous alterations to be made to the imported plan and resulting changes to be observed in continuous-time[12]. This continuity of sampling and quantifying cannot be obtained by a standard lattice, which depends on a discrete-time analytical process. Discrete-time process means that the system needs to be analysed in its entirety, and that any potential changes go through iterative and discrete levels of analysis. Thirdly, the continuous-time stochastic process has the potential to integrate analysis of inanimate spatial units as in the current method with future simulations of movement and agent interactions.

c. High levels of resolution of spectrum mapping

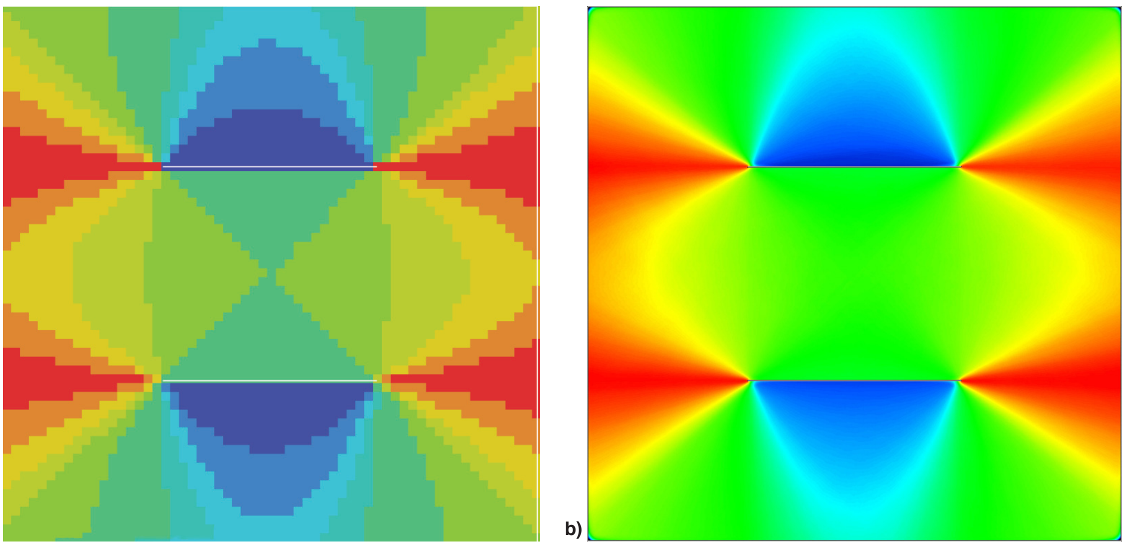
An additional benefit of the stochastic approach is high resolution of spatial mapping. The discretisation method in VGA dictates the resolution of the visual distribution of measures and mappings, since values are calculated and assigned per grid cell. High-resolution mappings require finer grids and therefore larger and more complex graphs resulting in far longer calculation times. The proposed stochastic system assigns and represents values to all points within isovists at the level of screen pixels, providing a high level of isovist field resolution. As a comparison, we provide two analyses of a simple hypothetical layout of two walls in a square space. Figure 7a shows VGA's assessment of connectivity based on a 60x60 grid. Figure 7b shows our version of the same. The former entails 3,600 distinct numeric values, whilst the latter consists of 547,600.

d. Geometric measures of isovists

We present four measures selected to bear comparison to those identified by Benedikt (1979), Batty (2001), Turner et al. (2001) and Conroy Dalton and Dalton (2001). In Figures 9-16 we provide an explanation of how these measures work in hypothetical examples.

Notes:

12 *Recently, increased computational power has allowed other approaches to implement isovist fields in continuous-time, linking design processes with analytical feedback (Schneider and König, 2012).*



a) b)

Figure 7:

Comparison of VGA and isovist mapping resolutions:

a) *VGA connectivity mapping for a grid of 3,600 cells.*

b) *Isovist connectivity for stochastic sampling of 2,500 points.*

Notes:

[13] This is a static measure. A linear relationship has been demonstrated between this measure and Turner's VGA 'connectivity' field values (with correlation of 0.8R^2).

i] Connectivity (C_v)

Connectivity accounts for the number of times a location 'V' occurs within isovists or is 'seen'. It is directly proportional to the number of points in space with which 'V' has a first-order connectivity. This measure is calculated by incrementing a count at 'V' whenever 'V' is found to be within an isovist, and is equivalent to connectivity as defined by Turner et al.[13] (2001).

ii] Co-visibility (I_v)

'Co-visibility' accounts for the mean area of all isovists 'V' is located within, and is measured by the sum of the area 'A' of all isovists containing 'V' divided by connectivity (C_v) at 'V'. It indicates the extent to which 'taking the next step' beyond the confines of a current isovist is likely to reveal greater or lesser visual area than currently available.

$$I_v = \frac{\sum_{i=1}^{n} A_i}{C_v}$$

Equation 1: Co-visibility

iii] Compactness (S_v)

'Compactness' accounts for the mean shape compactness (relative to a circle) of all isovists 'V' is located within. It describes the extent to which a step away from a current isovist is likely to reveal visual information with higher or lesser levels of convexity (or degree of intervisibility). It is calculated as the sum of the 'isoperimetric coefficient' (4πA) of all isovists that contain 'V', divided by connectivity at 'V'.

$$S_v = \frac{\sum_{i=1}^{n} \frac{4\pi Ai}{R^2}}{C_v}$$

Equation 2: Compactness

iv] Occlusivity (O_v)

Occluded radial lengths are those edges of an isovist that are not physically defined and reveal previously unseen space during movement. For each isovist we establish an 'occlusivity coefficient' of isovist area against potential area that could be revealed by such edges ('*R*', Figure 8), calculated as follows:

$$O_i = \frac{\sum_{j=1}^{n} R_j^2}{A_i}$$

Equation 3: Isovist 'occlusive coefficient'

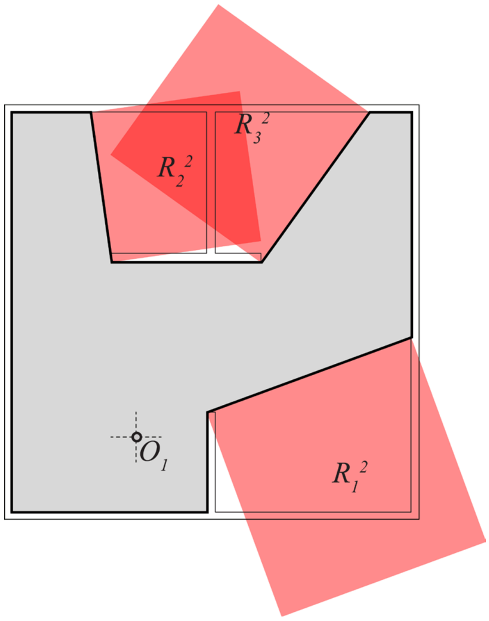
The measure of 'Occlusivity' is then calculated as the sum of the 'occlusivity coefficient' of all isovists that contain 'V' divided by connectivity (C_v). It accounts for the potential area that can be revealed through occluded radials within one visual step.

$$O_v = \frac{\sum_{i=1}^{n} O_i}{C_v}$$

Equation 4: Occlusivity

Figure 8:

Calculation of occlusive ratio; the sum of values of R^2 is compared to the isovist area.



The four measures are discussed here using eight hypothetical layouts[14] (Figures 9-16), followed by Mies van der Roher's Farnworth House (Figures 17-21). The former are laid out by locating a block centrally or close to an edge (Figures 9-11), experimenting with different shapes for the central block such as a cross and a T-shape (Figures 12, 13), and removing bars from these blocks to allow views through previously blocked regions (Figures 14-16). It is important to clarify that this section has mainly a methodological and illustrative purpose, rather than demonstrating the theoretical significance of the results in relation to spatial cognition.

Starting with the first series of layouts, Connectivity shows that by locating a block at the centre of the space, we maximise intervisibility of the points located at the four corners (Figure 9a). These points occur in most isovists and hence have high Connectivity values. The measure of Co-visibility (Figure 9b) identifies a diamond-shaped region circumscribing the central block and the locations of intersections of isovists of the highest areas in the layout. This makes sense, as the isovists of the highest Connectivity value generated from each of the four corners directly face two of the sides of the block intersecting at points located within the diamond-shaped area.

Since Co-visibility captures the extent to which a lesser or greater number of isovists overlap at a location, it follows that the higher the Connectivity of points one step away from a location, the higher the Co-visibility value of this location. High Co-visibility, therefore, is likely to take place within and in-between large regions of space. In Figure 9b where the block is placed centrally, there seems to be an inverse relationship of Co-visibility to Connectivity (with high values of Co-visibility located in the areas of low Connectivity and vice versa). Yet, the relationship between the two measures is not always one of inversion. When the block is moved closer to one or two of the outer edges (Figures 10b, 11b), high Co-visibility values occur in regions that are in middle and lower range of Connectivity shown in green on the left side of the central block (Figure 11b). This captures the fact that middle range Co-visibility values occur in proximity to isovists that have a large area still attracting a high number of overlaps, whilst low connectivity regions cannot.

Compactness captures the extent to which a point falls within isovists of high convexity. In many of the hypothetical cases (Figures 9c-11c, 14c), this nearly matches the values of Co-visibility. This seems reasonable, as isovists of large area tend to have a high level of intervisibility or convexity; therefore, the areas with large isovists frequently overlap (high Co-visibility) and are expected to have a high Compactness. Nevertheless, there is not always a match between Co-visibility and Compactness. Significant variations can be seen in Figures 15b, c and 16b, c. Routes through the central space, which show middle to high Co-visibility values (Figures 15b, 16b) have very low values in terms of Compactness. Whilst Co-visibility captures these routes as links between spaces of large area, Compactness shows that they function as a network of low convexity spaces.

Finally, Occlusivity demarcates the highest level of intersections of isovists of long occluded edges and seems to be in an inverse relationship with Compactness (Figures 9d-16d). This is because spaces with high levels of convexity (Compactness) are less likely to generate isovists with occluded edges and are more informationally stable. Long narrow regions (i.e. lower convexity) of low isovist areas that are close to large regions are likely to have a high number of occluded edges. Together these characteristics in isovists result in high levels of Occlusivity in their overlap. From these regions, an observer can see rapid changes of visual fields (Figures 14d, 15d). However, this is not always the rule. Variations are found, as in Figures 16c, d. In these cases, the region of very low Compactness

Notes:

[14] These contain 500,000 value points derived from 5,000 sample points. Legible fields are observed after running the system up to the selection of 300 sample points.

Figure 9 (left column)**:**

A centrally placed block and the resulting fields of:

a) *connectivity,*

b) *covisibility,*

c) *compactness,*

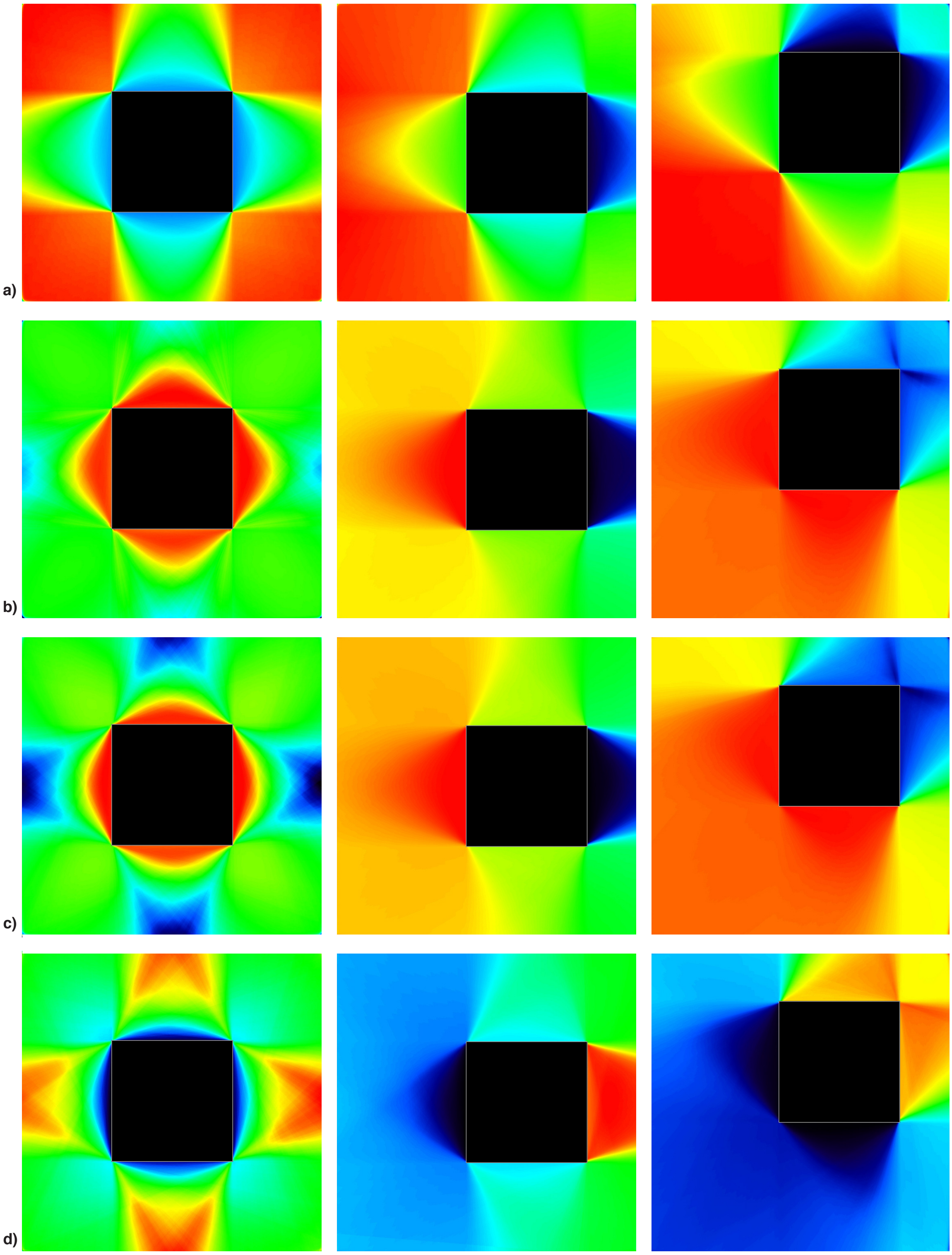
d) *occlusivity.*

Figure 10 (middle column)**:**

Variations on block locations and corresponding fields of same measures.

Figure 11 (right column)**:**

Variations on block locations and corresponding fields of same measures.



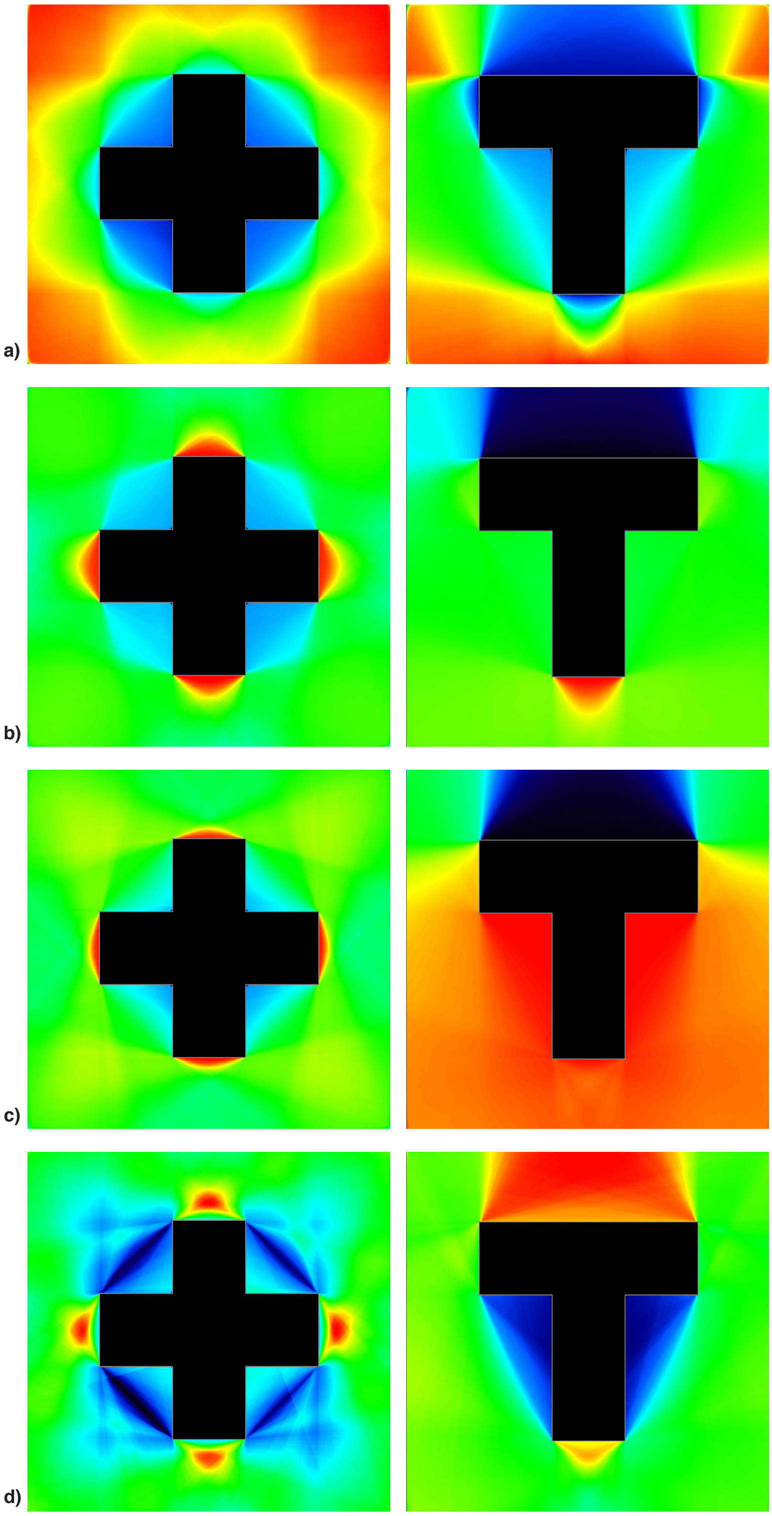


Figure 12 (left column)**:**

A centrally placed solid cross form and corresponding fields of:

a) *connectivity,*

b) *covisibility,*

c) *compactness,*

d) *occlusivity.*

Figure 13 (right column)**:**

Central solid 'T' form and corresponding fields of same measures.

Figure 14:

Two central bars and corresponding fields of:

a) *connectivity,*

b) *covisibility,*

c) *compactness,*

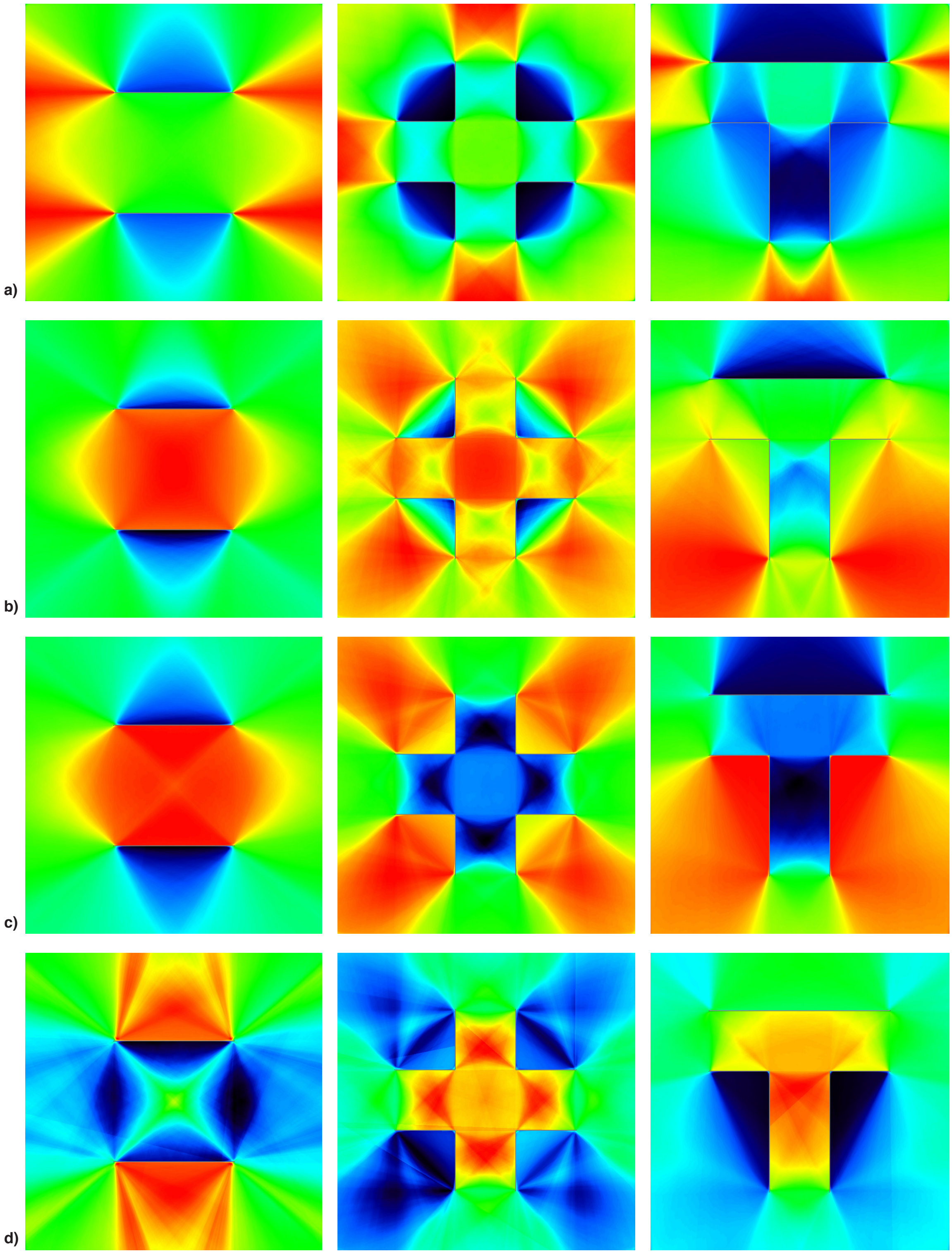
d) *occlusivity.*

Figure 15 (middle column)**:**

Bars removed from a central cross to allow vision through and corresponding fields of same measures.

Figure 16 (right column)**:**

Bars removed from a central 'T' to allow vision through and corresponding fields of same measures.



above the 'opened T' configuration has middle values of Occlusivity. This identifies a region between low convexity spaces but with relatively stable visual fields.

On the whole, the four measures seem to operate as complementary pairs of values. Co-visibility seems to mediate between a high and middle range of Connectivity values, in a way which captures the relative spatial distribution of intervisible and co-visible points in the layouts. Comparison of Co-visibility to Compactness illustrates the extent to which areas of intervisible locations arise from the ways in which convexity of isovists are distributed in a system. The third and final pair, Compactness and Occlusivity, describes how stability or change of visual information arises from the relational distribution of convexity (stability) and occluded edges (change) in an environment.

Moving to Mies van der Rohe's Farnsworth House (1951, Figure 17), we use the measures to describe the layout on its own (Figure 19), and with furniture (Figures 20-21). Described as a house with one room, the Farnsworth house is composed as a transparent horizontal slice of space between two slabs[15]. The interior is divided by a compact block - which accommodates the service spaces (kitchen, bathrooms and fireplace) - into four functional areas with a flowing relationship to each other. The block features as an object in the house, which in turn becomes an object in the landscape. Central to Mies' typology of the single-room-building is the placement of furniture as free-standing features in space. Turner et al. demonstrate that measure of clustering coefficient captures this 'nesting' of objects through a transformation of values occurring as one moves closer to the house and inside it, and draw relations with Peponis et al.'s e- and s- partitions (Figures 18a, b; Turner et al., 2001). It is interesting to compare their analysis with the proposed model with particular reference to objects and furniture. More importantly, we can use this analysis to address the research question of whether the insertion of the service block inside a single 'room' generates different functional affordances in the layout based on different degrees of visibility exposure.

Notes:

[15] The bottom slab features as a raised terrace, partly to respond to potential flooding of the nearby river, and partly to make the house appear floating in the setting.

Figure 17:

View of the Farnsworth House.

(From Wikimedia Commons)

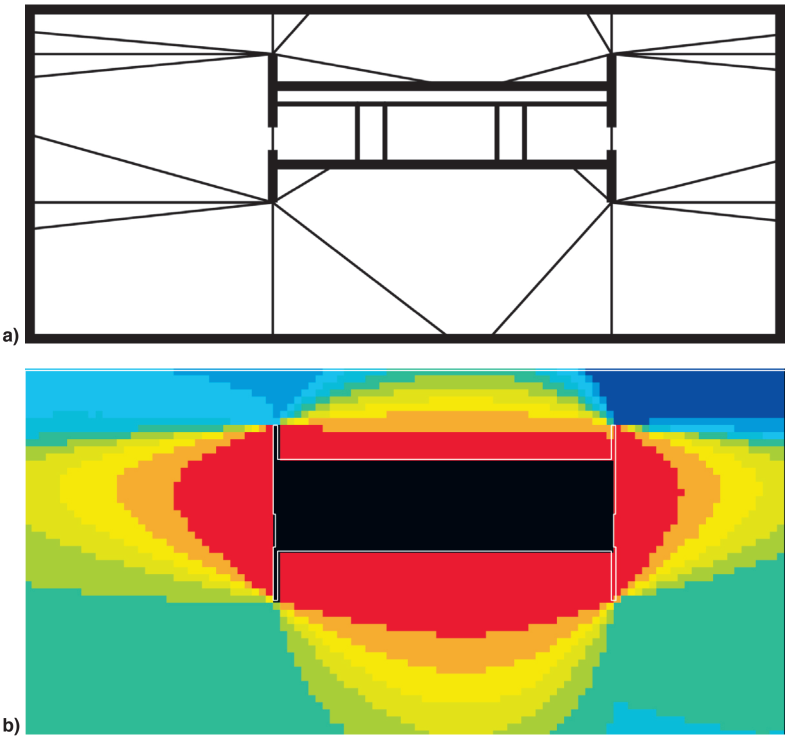


Figure 18:

a) *S- and e-partitions of the Farnsworth House (after Peponis et al., 1997).*

b) *Clustering coefficient of the Farnsworth House (after Turner et al., 2001).*

The results without furniture (Figures 19a-d) show that whereas the highest values of Connectivity highlight the two front ends of the building, those of Co-visibility concentrate in the central front area where the fireplace is located. This means that this area features in most views from different positions in its neighbouring regions. Compactness (Figure 19c) picks up the L-shaped-area stretching from the back left to the front right of the house through the distribution of high values and hence, high convexity throughout. Comparatively to the rest of the spaces, this area is seen in a sequence of isovists that are convex and informationally stable. Finally, Occlusivity (Figure 19d) highlights the kitchen area behind the block, in clear opposition to the living areas at the left, front left, front and front right of the house. This distribution indicates that the most continuous visual change occurs as one moves from the living area towards the kitchen.

Figures 20a-d and 21a-d demonstrate subtler differences in the distribution of values than those previously observed when furniture is included. Connectivity redefines the fireplace area as an area of privacy with low values (Figures 20a, 21a). In contrast, high values of Co-visibility are located immediately adjacent to objects and furniture (Figures 20b, 21b). The distribution of Co-visibility shows that these objects are seen from many different locations, punctuating visual fields and standing out as persistent features. The addition of furniture also inverts the patterns previously described by the measures of Compactness and Occlusivity (Figures 19c, d and 21c, d). With the introduction of objects, the living areas shift from high to low values of these measures, capturing the breaking of convexity due to furniture.

In response to the questions raised earlier about the Farnsworth House, we see that individually

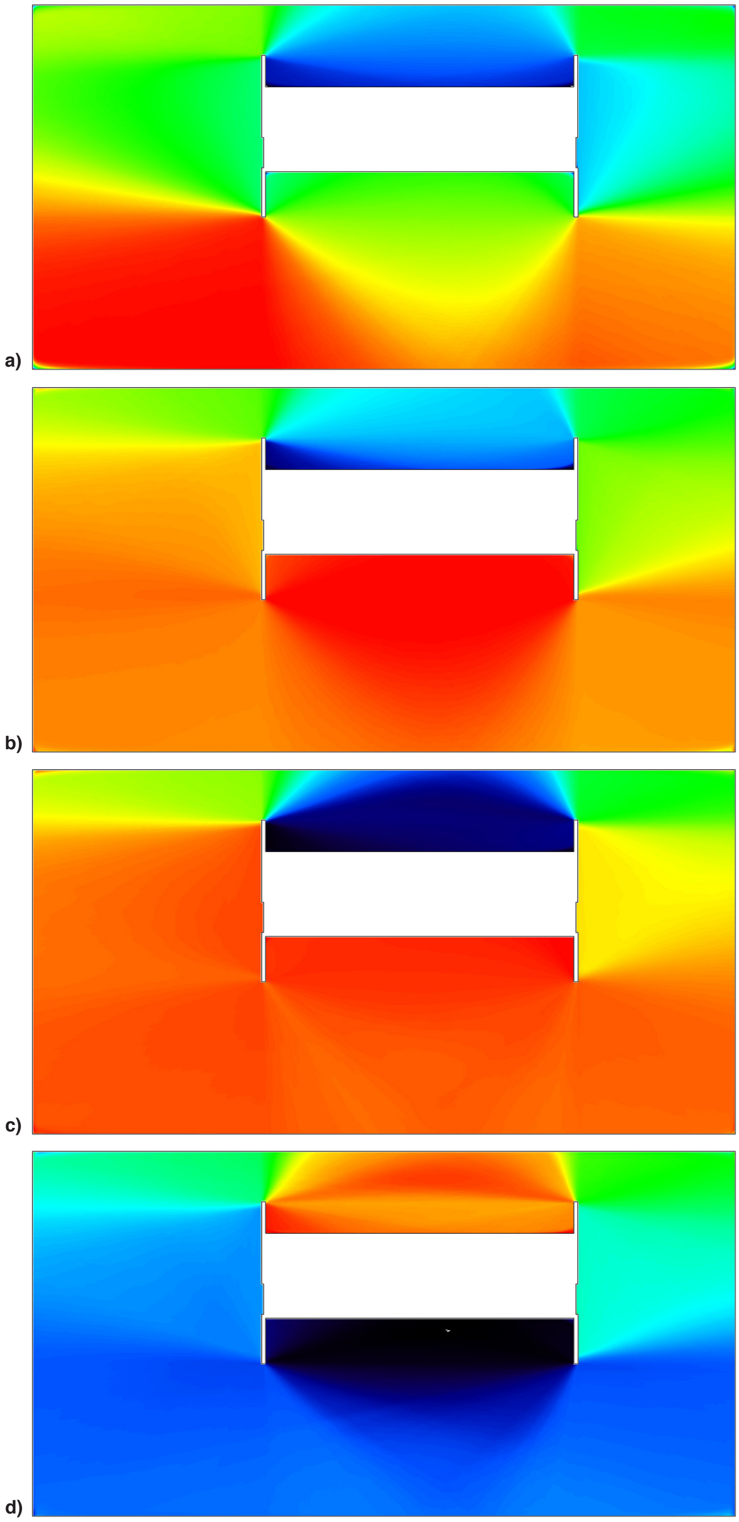


Figure 19:

Farnsworth House, basic configuration, resulting fields of:

a) *connectivity,*

b) *covisibility,*

c) *compactness,*

d) *occlusivity.*

Figure 20:

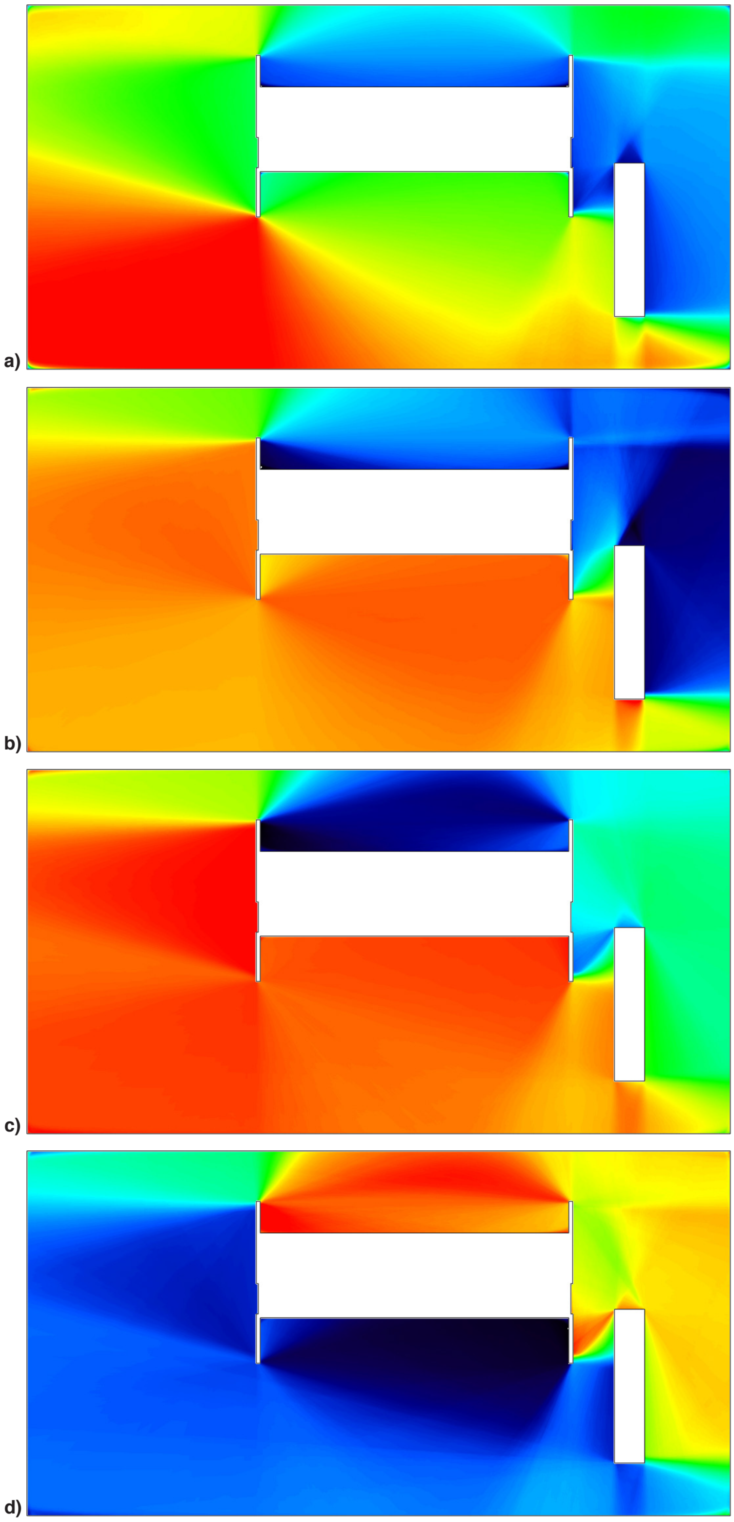
Farnsworth House, secondary configuration and corresponding fields of:

***a)** connectivity,*

***b)** covisibility,*

***c)** compactness,*

***d)** occlusivity.*



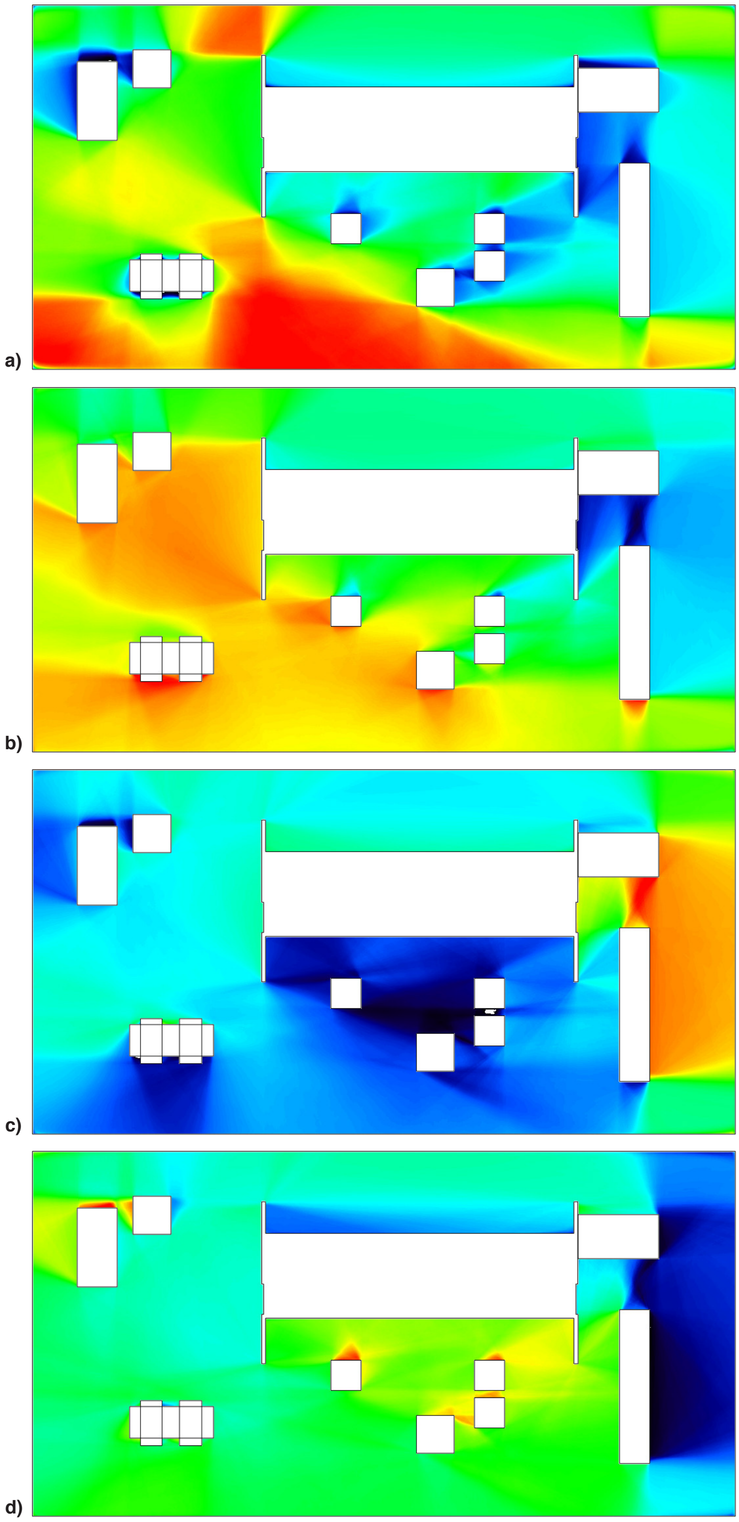


Figure 21:

Farnsworth House, furniture configuration and corresponding fields of:

a) *connectivity,*

b) *covisibility,*

c) *compactness,*

d) *occlusivity.*

and in complementary pairs the measures seem to express the *functional significance* of certain regions in the house, such as the hearth area. The repetitive presence of this area in isovists due to high Co-visibility values (Figure 19b) expresses a certain kind of 'centrality' related to optical experience. This centrality is in tension with the lower values of Co-visibility in this same area when furniture is included in the analysis (Figure 21b). The tension between the results from the two levels of analysis seems to express a compositional tension between the entire spatial field of the house (divided by the service block) and the objects that are located inside it. Another functional expression articulated by Connectivity and Co-visibility values concerns the diagonal stretch that distinguishes the living areas from the kitchen and bedroom (Figure 21b). In relation to previous kinds of analysis, the proposed measures in Figures 19a-c capture functionally different areas modulated by the block and the furniture. In contrast, the measure of clustering coefficient is almost equally distributed around the central block (Figures 18a, b).

The proposed measures and their relationship to other types of analysis need further testing. A first observation that arises from the complementarity of measures at this preliminary stage, however, is that seeing areas of high Connectivity values in layouts comes along with registering relations of Co-visibility located in-between high Connectivity areas, and vice versa. A second observation is that due to high resolution, the distribution of values captures s- and e- partitions, suggesting that latent geometries of spatial subdivision are not simply dictated by built shape as suggested by Turner et al. Instead, there is a relational logic between *microscopic* properties of spatial locations, and *macroscopic* characteristics of the environment captured by isovist geometry and built shape, such as area, overlap, convexity, boundaries and occluded edges. The underlying suggestion is that embodied vision and embodied projection register and infer actual and virtual topologies and Euclidian geometries of space, built shape and vision, and their complementary logic.

4. Discussion and future work

We have presented a new approach to isovist analysis based on a continuous-time stochastic process for root isovist sampling, isovist generation and quantification of geometric isovist values. This approach stems from the recognition that VGA has certain disadvantages. The first is that the intuitive and relational aspects of isovists are discarded together with their geometric logic. The fact that points in space belong to isovist frameworks, which include network-like elements of topology and Euclidian geometry, is equally important as graphing the entire structure of a layout. The second drawback is that VGA graphs an entire map of what is seen and accessed through time, in which integration (mean shortest path length) is normally interpreted as guiding aggregate movement along certain paths. However, first-time viewers discover the shortest paths only after they experiment with movement and vision as temporary states. The third disadvantage is that VGA is based on discrete-time iterative process, so that there is no continuous-time integration between analysis and design, or of different features, such as spatial analysis and agent simulation.

In opting for isovists rather than graphs and assigning isovist values to all points within an isovist rather than to the origin, this model significantly extends Benedikt's and Turner et al.'s approaches. It retains isovist geometry and constructs spectrum variation of geometric measures at isovist intersections in continuous space. The system resolves the problem of resolution at the level of input of grid size and output of measures through a continuous-time stochastic process. Finally, it generates probabilistic fields of spatial description that account for average potentiality occurring in one-step movement or the next isovist around the corner in all directions. The tool allows for alterations to the plan to be observed in continuous time, and has the potential to integrate additional features into a single platform in the future.

In terms of limitations, the method has focused on 360-degree 'undirected' vision and it would be useful to also consider directed isovists. We acknowledge that as different directions will usually lead to movement around different corners, the differential potentiality can be of more interest than the average potentiality in calculations in the future. In addition, the relationship between measures we have observed need quantitative explanation, as explanations are limited at the level of visual distribution of results.

At the beginning of the paper we stress the gap between situated vision and all-to-all graph relations, and explain that this is largely due to underlying gaps in available diagrams and models. We propose that a new isovist methodology with the potential to explain the relationship between situated vision and global structure in layouts should reconceptualise isovists beyond discrete units, and reformulate them as seeds for an extended framework of spatial knowledge. The first step in overcoming this gap is to model and diagram embodied vision as a probabilistic continuous-time process. The second step is to consider a system of actually and virtually occupied spatial points through hypothesis and projections along the structure of possibilities embedded in isovist relations. Equally significant to local and global graph measures are relations that lie one step from us at each point, and so are in a state of having been encountered, or feature instead as possibility, remaining un-actualised (Psarra, 2013).

At the more general theoretical level, we propose the need to reconceptualise the relationship between the observer, embodied vision and the environment. The underlying suggestion is that the distinction between two states, local and global, and the mathematical expression of their relationship (intelligibility) has been proved useful, but externalises the link between embodied vision and global structure and makes it static. Further, the distinction between perception (normally associated with local relations) and spatial cognition (associated with global properties) in space syntax research is fundamentally Platonic in nature. This is because it sees cognition as an abstraction captured by global structure, and perception as locked in the empirical world of observation and the senses. This distinction disembodies cognition and reduces perception to mere information. In order to address the dynamic nature of the observer and space we need to reconceptualise both embodied vision and the structure of a spatial complex as spatial knowledge *in process* rather than as states at the opposite ends of information and structure. This has the potential to facilitate understanding of the process of discovery not as '*an accumulation of perceptions….aggregated into a picture of the whole'* (Hillier, 2003), but as emergent and evolving spatial knowledge subject to hypothesis testing and embodied projection. This remains to be tested.

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Endnotes

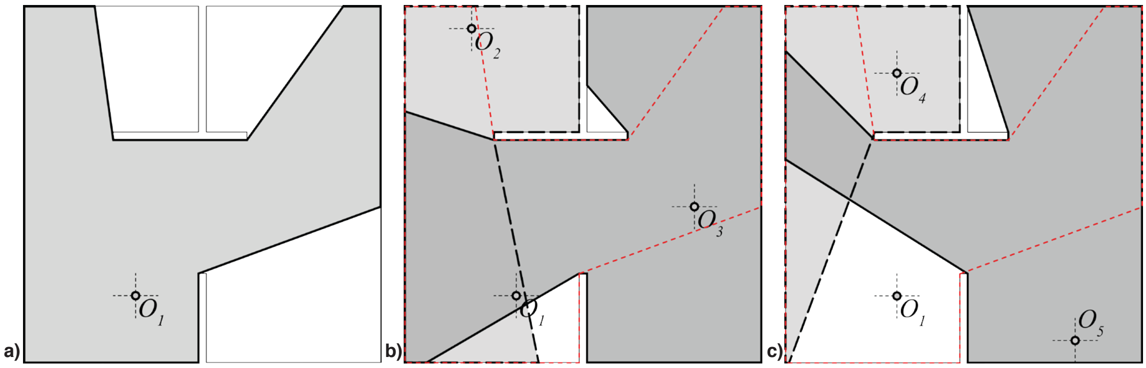

Figure 22:

a) *Isovists of accessible (light grey) and visible space (dark grey). Plane W can be seen through.*

b) *Isovist of reflected space (dark grey). Plane W is reflective.*

c) *Isovist of specular space (dark grey). Plane W is reflective.*

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