Article

Urban Analytics and City Science

EPB: Urban Analytics and City Science
2019, Vol. 46(5) 948–962

DOI: 10.1177/2399808317739893
journals.sagepub.com/home/epb
SAGE

Three-dimensional visibility graph analysis and its application

Yi Lu
City University of Hong Kong, Hong Kong

Zhonghua Gou
Griffith University, Australia

Yu Ye
Tongji University, China

Qiang Sheng
Beijing Jiaotong University, China

Abstract

Graph-based visibility analysis, developed from space syntax and social network theory, embraces mutual visibility between locations in a spatial system. It helps designers and researchers to decode spatial cognition and behavior, but methodological constraints limit its application to two-dimensional floor plans. In this study, we propose a new visibility graph analysis that can be used in three-dimensional built environments, such as multilevel atrium buildings or urban environments with canopies or overpass bridges. Furthermore, we draw a distinction between a *generic visibility graph* and a *targeted visibility graph*. In the former, an occupiable location is considered as both the origin and target of visibility lines. In the latter, we further take into account the visible space or specific targets in a system. Visible locations are spaces people can see but cannot necessarily physically occupy. With this differentiation, the visibility graph system is more amenable to new applications in three-dimensional architectural and urban design while retaining a mapping back to the original two-dimensional *visibility graph* method through the *generic visibility graph*. Four examples illustrate the application of the proposed visibility graph analysis in complex three-dimensional building and urban environments.

Keywords

Visibility graph, three-dimensional space, space syntax, multilevel buildings, urban analytics

---

Corresponding author:
Yi Lu, Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong.
Email: yilu24@cityu.edu.hk

Introduction

Visibility analysis has proved useful in investigating urban and building environments for many reasons. It allows us to understand the built environment's spatial and visual relations, which regulate human movement, afford social interactions, create interesting vistas, and highlight salient landmarks (Hillier and Hanson, 1984; Turner et al., 2001). Visibility analysis also allows us to make rigorous mathematical descriptions of systems, and hence enables us predict the inhabitants' experience in urban and building environments with reasonable certainty.

Analytical visibility models have been offered from various fields, e.g. architecture, urban planning, landscaping, and computer science. Among them, *visibility graph analysis* focuses on mutual visibility between locations and has been widely used in the urban planning and architectural fields. Yet *visibility graph analysis* only deals with two-dimensional (2D) spaces and cannot deal with complex three-dimensional (3D) environments, such as multilevel atrium buildings or urban environments with canopies or overpass bridges. We thus propose 3D *visibility graph analysis* on a geographic information system (GIS) platform and further introduce *targeted visibility graph analysis* by considering visible location or specific targets in a setting.

The previous research

Methodological development of visibility analysis. Visibility analysis has a long history in the architecture and urban planning fields. One of the seminal studies is Benedikt's concept of an isovist (i.e. the set of all points visible from a given vantage point) and an isovist field (i.e. a set of contour lines representing analytic measures that quantify certain properties of the isovist from all points in the setting) (Benedikt, 1979). Benedikt further suggested that isovists and isovist fields are related to Gibson's model of visual perception because they capture the variation of visual fields that informs the spatial understanding of a person moving in an environment (Gibson, 1979). Later, many studies developed various measures and computational methods based on the concept of isovist. For example, Batty (2001) offered a computational scheme for defining and measuring isovist.

Turner et al. (2001) proposed an innovative visibility analysis method, *visibility graph analysis*, by drawing on graph-based representation from space syntax (Hillier and Hanson, 1984) and social network theory (Watts and Strogatz, 1998). It embraces mutual visibility between locations, and Turner and his colleagues argued that the mutual visibility may have potential social interpretations. All occupiable space in any 2D floor plan can be represented as a grid of points of equal distance, e.g. 0.3 m. Those points form the nodes in a graph; the mutual visibilities between the points form the edges in a graph. Hence, a spatial environment can be represented as a graph of mutual visible points, also referred to as a *visibility graph*. Through this representation, Turner and his colleagues further developed local and global visual properties. A node's local properties depend on the relation to its immediate connecting points, whereas its global properties depend on the relations to all nodes in a system. The *connectivity*—also called *degree centrality* in graph theory—is a local property because it measures the number of immediate connecting points in a graph. The *mean depth*—the inverse of which is called *closeness centrality* in graph theory—is a global property because it measures the average graph-based path distance that needs to be traversed to get from a node to all other nodes.

Researchers from the fields of geography, architecture, and urban planning have also explored 3D isovist. Several studies have developed the 3D isovist algorithms and assessment tools (Fisher-Gewirtzman et al., 2003; Koltsova et al., 2013; Morello and

Ratti, 2009; Suleiman et al., 2013). Some studies have examined the topics such as enclosures or openness (Fisher-Gewirtzman, 2016; Fisher-Gewirtzman, 2015; Shach-Pinsly et al., 2006; Stamps, 2005), visible sky (Yang et al., 2007), visible water (Fisher-Gewirtzman et al., 2005), pedestrians' visual experience in urban environments (Chamberlain and Meitner, 2013), or representation methods (Dalton and Dalton, 2015). Such studies have normally focused on various local properties of individual 3D isovists, including the size of visible sky, length of longest sight line, or distance to closest objects. However, in 3D isovist analysis, graph-based visibility analysis has still not been directly explored.

Application of visibility graph analysis. The analytical measures from a visibility graph can be closely associated with how a person understands a building layout and the objects on display. Therefore, *visibility analysis* is of particular interest in museum studies. Such studies have often focused on the relationship between museum layout and the structure of visitor paths (Choi, 1999; Hillier and Tzortzi, 2006; Psarra, 2005). Choi (1999) reported than in six out of eight museum floors studied, the number of displayed objects visible from a space was correlated to the number of visitors whose chosen paths went through that space. This indicates that visitors' selection of paths is influenced by the visual relations between spaces and displays.

There is also sufficient interest in the larger cognitive, pedagogical, and cultural functions of museums. Some studies reported that the museum layout and display setting influence visitors' exploration patterns and potential narrative understanding (Peponis et al., 2004; Psarra, 2009; Tzortzi, 2004). For example, Peponis and his colleagues found that visitors' awareness of individual free-standing exhibits was associated with the exhibit's visual accessibility (i.e. the *connectivity* and the *mean depth*) and that active engagement with these exhibits was associated with the *inter-visibility* of individual exhibits (Peponis et al., 2004). Newhouse's work on the relationship between the placement of the Winged Victory of Samothrace in the Louvre, the manner in which visitors approached and viewed it, and the meanings conferred by the successive exhibition settings is another significant study in this regard (Newhouse, 2005).

Patterns of co-visibility were also the focus of attention in an analysis of the changing interior design of the second floor of the High Museum of Art in Atlanta, GA (Zamani and Peponis, 2010). Measurable changes in interior design reflected underlying changes in the intentions of curators. More specifically, the original 1983 design afforded rich patterns of co-visibility across physical and classificatory boundaries; the 1997 design framed sets of displays according to definite themes chosen by the curators and almost totally excluded any co-visibility; the design of 2003 afforded rich patterns of co-visibility, but these were contained within floor-plan units devoted to the same class of displays.

Lu and Peponis (2014) showed that visitors' assessment of the clarity of the presentation of a pictorial theme is associated with the degree of co-visibility of member works in virtual exhibition environments. They also showed that visitors can effortlessly identify locations and orientations that maximize the co-visibility of member works. These findings confirm that visitors are sensitive to patterns of display co-visibility.

Research gaps

Despite advances in the methodology and algorithms of *visibility graph analysis*, previous studies have two major limitations. First, *visibility graph analysis* and the corresponding software Depthmap developed by Turner cannot deal with 3D environments. Some researchers try to overcome this constraint by manually linking vertical connections (e.g.

staircase or elevator) in different floor plans (Hölscher et al., 2012). Yet this solution is rendered ineffective in a complex 3D environment affording ample visibility between different floors, such as in a multilevel building with an atrium or courtyard.

We propose an approach of 3D *visibility graph analysis* on a GIS platform, which can overcome this shortcoming. Varoudis and Psarra (2014) indeed already proposed 3D visibility graphs, although they solved the problem in Sketchup and used a different theoretical framework from ours. A more detailed comparison will be presented in the Discussion section.

Second, most visibility analysis focuses on generic visibility, which is visibility to all open spaces, and may understate the impact of cognitively salient components in a spatial system. A growing body of empirical studies has established that the visibility towards some objects or elements may better account for difference kinds of cognitive processes and behaviors. For example, the visibility of displays in museums affects visitors' movement, engagement, and experience (see section "Application of visibility graph analysis"); the mutual visibility of commonly used destinations affects passengers' ability to find their way in airport terminals (Churchill et al., 2008; Lam et al., 2003); the visibility of corridor intersections in buildings or of landmarks in urban environments affects peoples' wayfinding search behaviors (Haq and Zimring, 2003; Omer and Goldblatt, 2007).

In the context of urban and built environments, we argue that the visual information about cognitively significant elements or targets could facilitate our understanding of how people perceive and behave. The approach of 3D visibility analysis towards those targets is referred to as *targeted visibility graph* analysis in this study.

The *targeted visibility graph* is also supported by Gibson's affordance theory. Gibson wrote that the relationship between humans and their environment is reciprocally defined through affordances, which are what the environment offers, benefiting or harming people (Gibson, 1979). They are the functionally significant properties of an environment with respect to habitual users. Gibson further suggested that affordances and other visual information are directly perceived and that it is a process of perceiving a "value-rich ecological object" rather than a "value-free physic" (Gibson, 1979: 140). There have been some attempts to apply analytical visibility analysis to certain targets in 2D floor plans; yet they only produced some limited measures, e.g. the number of visible targets in a setting (Lu and Peponis, 2014; Lu and Seo, 2015; Lu and Zimring, 2012).

Present study

People, especially urban residents, experience numerous various 3D built environments. Atriums or courtyards are often key areas for both buildings and cities, such as in transport interchanges, museums, or libraries. These 3D spaces offer natural light and ventilation, create continuity to urban space outside, or provide spatial orientation. However, one of the widely accepted visibility analysis techniques, *visibility graph analysis*, is incapable of handling complex 3D environments.

We propose both a *generic visibility graph* and a *targeted visibility graph* for 3D environments. The computational development is described in the next section and four examples are used to illustrate their applicability in both building and urban environments.

Methods

Constructing a visibility graph of a 3D spatial environment involves two related decisions. First, we must select an appropriate set of visibility-generating locations to form the nodes of the graph. Second, we need to separate the spaces that people can occupy and the spaces that people can see; the relation between these two types of spaces should be distinguished in the graph. A common strategy used by architects and urban designers is to highlight the difference between what people see and where people can go by providing 3D visual fields over large open spaces, such as atriums or courtyards.

We offer two options in this study: a *generic visibility graph* and a *targeted visibility graph*.[1]

(1) The first option focuses on only the set of spaces that people can occupy, referred to as occupiable spaces. This option simplifies the relation between occupiable spaces and visible spaces by downplaying volumetric visible spaces. In essence, it is similar to the previous 2D visibility graph, where occupiable spaces are both the origin and the target of visibility lines in the graph (Turner et al., 2001). This approach is suitable for 3D environments, where the spaces on different floors are largely horizontal and planar. It also fits the situation in which occupiable spaces are the research focus.

Drawing on Turner's method, all occupiable spaces in a 3D environment, such as all floor surfaces in a multilevel building, can be represented as a grid of points of equal distance. Those points form the nodes of the *generic visibility graph*; the mutual visibility between them forms the edge of the graph. It is worth noting that observation points covering occupiable spaces can be set at human eye level above the floor surface to imitate what can be seen by a person. The human eye level may vary according to different postures, such as 1.7 m for standing, and 0.7 m for sitting.

After constructing the 3D *generic visibility graph*, two values, similar to their 2D counterparts, can be offered: connectivity (degree centrality) and integration (closeness centrality). Connectivity is a local visual property of a node in the graph, and it presents the number of immediately connecting nodes from that node. Integration is the normalized value of the sum of shortest graph-based path distance from a node to all other nodes in the graph, which can be shown as:

$$Integration_x = \frac{N-1}{\sum_{y \neq x}^{N-1} Distance(y, x)}$$

where N is the total number of nodes in the graph and *Distance* is the shortest graph-based path distance between nodes x and y in the graph. Integration is a graphical measure of closeness centrality.

(2) The second option draws a distinction between occupiable spaces and visible spaces or targets in a setting. Visible spaces are the spaces people can see that are not necessarily accessible, such as atriums, voids, or any large open spaces above people. Occupiable and visible spaces can be tessellated and represented by a 3D grid of points of equal distance, referring to occupiable points and visible points, both of which constitute the nodes in the graph.

The second decision that needs to be made is to how to regulate the relations of occupiable and visible points in the graph. We used edges in the graph to achieve the regulation (Figure 1). Three types of visibility relations exist: visibility between two visible points (e.g. V1–V2 in Figure 1), that between two occupiable points (e.g. O1–O2), and that between one occupiable point and one visible point (e.g. O1–V1). People can only reach

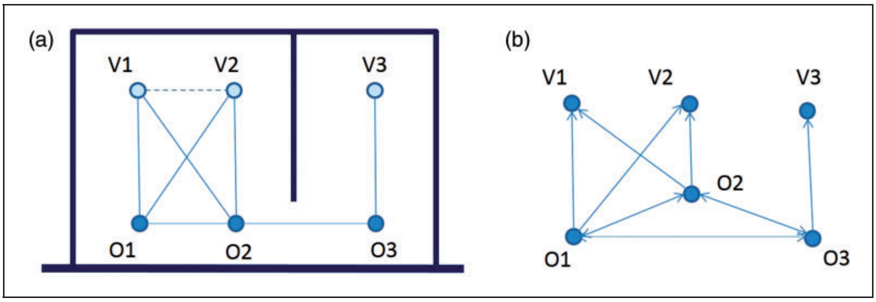

Figure 1. (a) As shown in a building section, a spatial system consists of occupiable spaces (tessellated into points O1, O2, and O3) and visible spaces (tessellated into points V1, V2, and V3). In the graph, all points are considered as nodes; only visibility between occupiable points and that between occupiable and visible points are considered as edges in the graph. The visibility between visible points is excluded in the graph (e.g. V1–V2, as shown with the dotted line). (b) The graph representing the spatial system.

occupiable spaces but not necessarily visible spaces; hence, only the O1–O2 and O1–V1 visibility relations are considered as edges of the graph. The mutual visibility between visible spaces is excluded in the graph. Furthermore, the visibility between one occupiable point and one visible point (e.g. O1–V1) is considered a one-way connection in the graph (from O1 to V1).

The separation of occupiable and visible spaces is essential in establishing a *targeted visibility graph* in which the observation points and target points are different. Given the definition of *targeted 3D visibility graph*, all points in visible spaces (e.g. points O1, O2, and O3) can be regarded as a particular form of targets. Other targets can also be used instead of visible spaces in the analysis. For example, in museums, displays can be considered as targets (O1, O2, O3 can represent three displays); in urban environments, landmarks; in shopping malls, store signs. The targeted visibility emphasizes visibility towards salient targets that may influence a person's cognitive process and behaviors.

After constructing the *targeted 3D visibility graph*, three values can be offered: targeted connectivity, targeted connectivity index (degree centrality), and targeted integration (closeness centrality). Targeted connectivity presents the number of immediately connecting targets from that node or the number of directly visible targets in a spatial system. The targeted connectivity index is simply the ratio of the number of visible targets and the total number of targets. It can be used to compare points from different systems with different numbers of targets.

$$Targeted\_Connectivity\_Index_x = \frac{Number\_of\_visible\_targets_x}{M}$$

where M is the total number of targets in the graph.

The integration is the normalized value of the sum of the shortest path distance from a node to all other targets in the graph, which can be shown as:

$$Targeted\_Integration_x = \frac{M}{\sum_t^M Distance(t, x)}$$

where M is the total number of targets in the graph and *Distance* is the shortest path distance between node x and target t in the graph.

The *generic visibility graph* and *targeted visibility graph* are both related and distinct. The two approaches implement the principle that people occupy only occupiable spaces. The *generic visibility graph* can be regarded as a specific form of *targeted visibility graph* if occupiable spaces are also visual targets. Hence, a *generic visibly graph* emphasizes the role of occupiable space, whereas a *targeted visibility graph* is more versatile and may be applied in a broader range of research scenarios. In the following section, we use four different examples to demonstrate how this approach may help us investigate 3D architectural and urban design.

Case studies

A T-shaped geometry

The first example demonstrates that a 3D visibility graph is sensitive to the height change of a T-shaped geometry. In Figure 2, a solid T-shaped geometry occupies the middle of a cubic space. The remaining void space is tessellated into a 3D grid of points of equal distance; the points at the lowest horizontal level are considered as occupiable space and all points are considered as target points. A targeted visibility graph is constructed accordingly.

The analysis shows that for two spatial systems with the same floor plan, the *targeted connectivity index* and *targeted integration* values decrease as a function of increased height of the solid T-shaped geometry. Hence, our analysis extends the Turner et al. (2001) method to 3D spaces and can quantify the visual accessibility of any 3D spatial system, simple or complex.

House NA

Architecture has a long history of distinguishing between the space we can see and the space we can physically access. Common design strategies include providing a large open atrium or courtyard, or providing ample visibility across different rooms or different floors. As a built example, we chose House NA, designed by Japanese architect Sou Fujimoto. Based on the concept of living in a tree, the house comprises 21 individual floor plates located at different heights and mostly transparent interior partitions. Those design features may provide intimacy for the client, a young couple, while also accommodating a group of guests by distributing people across the house. As the architect stated, "the intriguing point of a tree is these places are not hermetically isolated but are connected to one another..." (Frearson, 2012). The house was designed to facilitate social interaction through both visual and physical accessibility. The first question we ask is whether the house has homogenic visual accessibility across all spaces. If the answer is no, then the second question is whether the architect was aware of the difference and arranged programs accordingly.

We used a *3D generic visibility graph* to find out which space was visually closest to or furthest from the others in the system (Figure 3). We tessellated all spaces into a grid of points, which were treated as both observation points and target points because all spaces in this house were relatively low and accessible by people with different postures, such as sitting, standing, or lying down. The results showed that the most visually accessible points were in the lower-middle part of building, whereas the least visually accessible points were mainly in the top of the building. Most interestingly, the architect also assigned the most visually accessible spaces as living spaces requiring less privacy and assigned visually separated spaces as bedrooms requiring more privacy. The comparison indirectly confirms that this architect was conscious of the visibility patterns between the 21 floor plates, and our model provides useful mathematic descriptions of those spatial qualities.

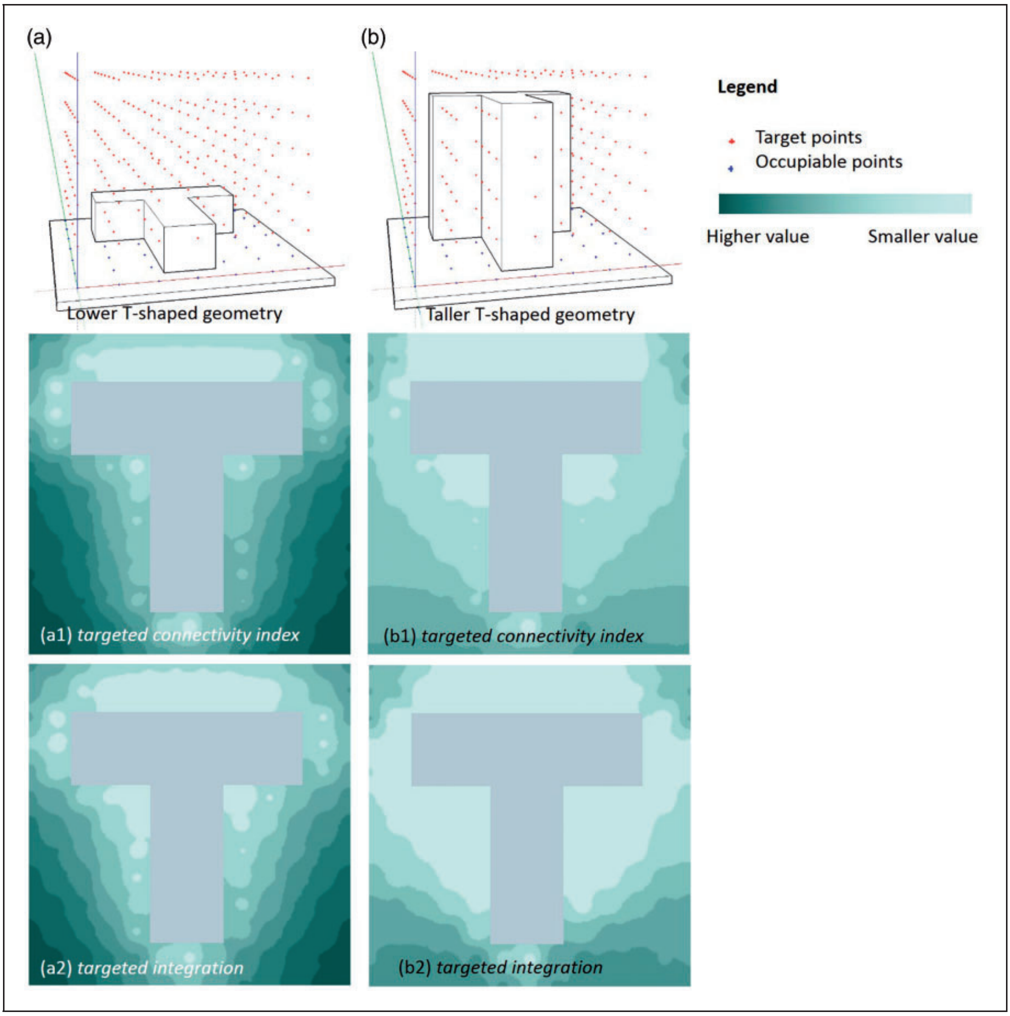

Figure 2. (a) A T-shaped geometry located in a cubic space, which is tessellated into a grid of points (red points). The lowest level of points is considered as occupiable points (blue points). (a1) The targeted connectivity index of occupiable points in system A (using the technique of inverse distance weighted in ArcGIS to interpolate values for locations between occupiable points). (a2) The targeted integration of occupiable points in system A. (b) The same spatial system with increased height of the T-shaped geometry. (b1) The targeted connectivity index of occupiable points in system B drops compared with that in system A. (b2) The targeted integration of occupiable points in system B also decreases.

Shopping mall

We can also extend the 3D visibility analysis beyond a qualitative discussion of spatial description. In a separated study, we showed that peoples' choice of spatial location can be predicted by objectively measured 3D visibility analysis (Lu and Ye, 2017). In that study, 19 participants were asked to identify the location where they can see the maximum number of stores simultaneously with 360 degrees of view in a multilevel mall.

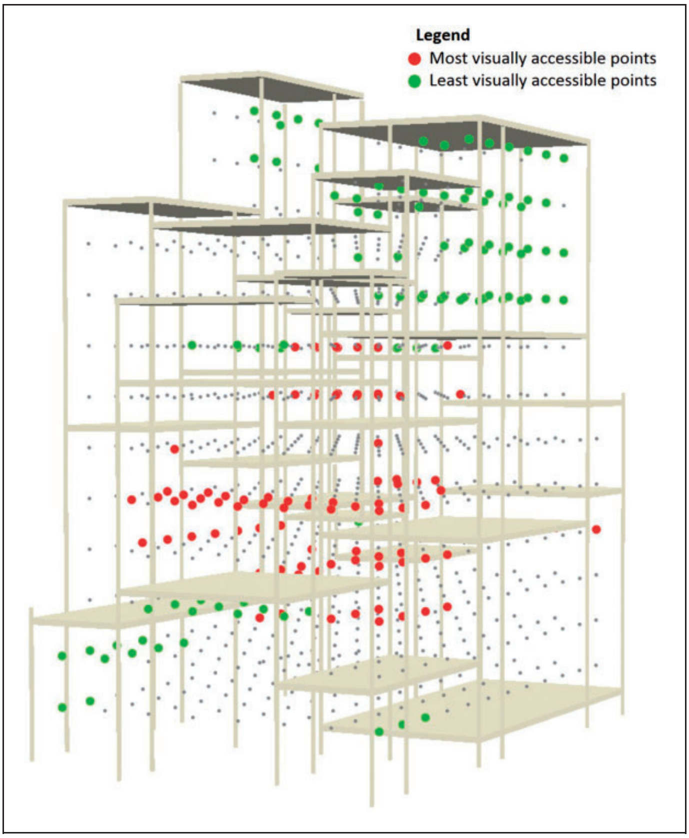

Figure 3. The generic visibility analysis of House NA. The most visually accessible spaces are represented by the points with the top 10% integration value (red dots). The least visually accessible spaces are represented by the points with the bottom 10% integration value (green dots).

The shopping mall comprised 220 stores on six floors and featured five large atriums. Most people selected the locations close to the central atrium in the first three floors (Figure 4a). Given the complexity of spatial configuration and presence of numerous stores in the mall, it is impossible for a person to physically visit all locations and compare the number of visible stores in the mall. People thus, need to predict what is visible from unvisited locations and the predictions is constantly corrected and updated after visiting. The predication and comparison of 3D perceptual information, which was involved in this search task, demonstrated that people are sensitive to the 3D perceptual information (Lu and Ye, 2017). The consistence in people's selected locations revealed that people can effectively remember, anticipate and compare 3D perceptual information (Figure 4a). A logistic regression model showed that the targeted connectivity to stores (Figure 4b), which is the number of visible stores at each location, is positively associated with the selected vantage locations by our participants (chi square = 31.96, $p < .001$). The results support Gibson's theory of affordances, in which salient targets in a spatial system can be cognitively registered by people. Although the example obviously simplifies any interaction between individuals and the built environment, it clearly shows that

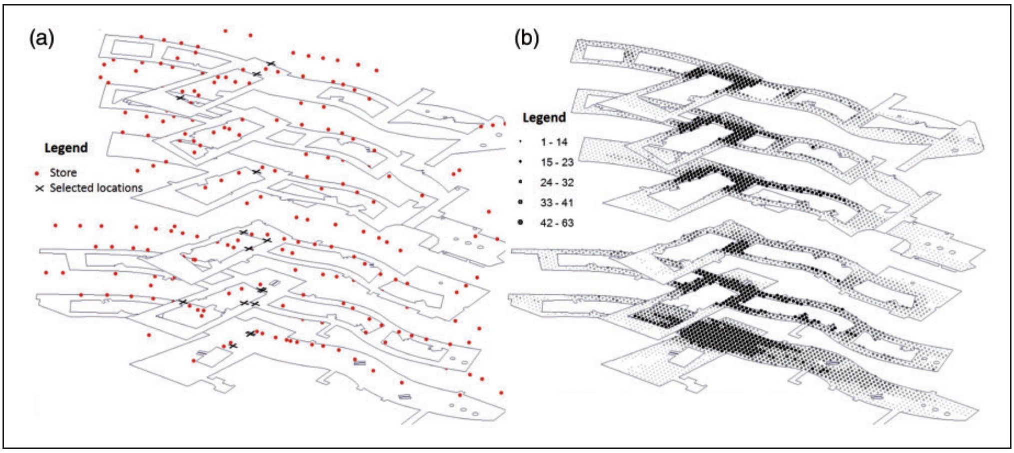

Figure 4. (a) The stacked floor plans of public spaces in a shopping mall. The mall has 220 stores and five large atriums, providing adequate visual access across floors. The participants were asked to locate a vantage point where they can see a maximum number of stores in the mall (including those on other floors). (b) The targeted connectivity to stores is positively associated with the selected vantage points.

simple analytic visibility models may predict human understanding of complex 3D environments.

Campus landmarks

In this example, we demonstrate the 3D visibility graph's application in an urban setting with uneven terrain. As the evidence began to accumulate, it was confirmed that peoples' spatial cognition and wayfinding behavior was at least partially affected by the mutual visibility between landmarks in both urban and building environments (Churchill et al., 2008; Haq and Zimring, 2003; Lam et al., 2003; Omer and Goldblatt, 2007). Yet most researchers manually assess those mutual visibilities.

This example shows a university campus in Hong Kong comprising many buildings connected by a network of walkways in a hilly site. The GIS data were obtained from the government, and the 3D spatial system was constructed with information about building footprint and height (Figure 5). In an exemplar scenario, there are six salient statuses acting as landmarks on the campus, and a researcher wants to explore how the visibility of those landmarks influences wayfinding behavior. To address this issue, we first create a series of observational points at equal distance (e.g. 10 m) along all walkways. The six statuses are used as targets in the targeted visibility graph. Thus, both the *targeted connectivity* and *targeted integration* can be obtained from our 3D visibility graph method. The *targeted connectivity* refers to the number of visible statuses from an observation point. The *targeted integration* refers to the normalized value of the sum of shortest graph-based path distance (based on visibility relations) from an observation point to all statuses in the graph. The *targeted integration* measures the degree to which a location is close to all targets in the system. As shown in Figure 5, both values can be visualized for every observational point by the point size. The observation points in the higher part of the campus generally have larger *targeted connectivity* and *targeted integration* than those in

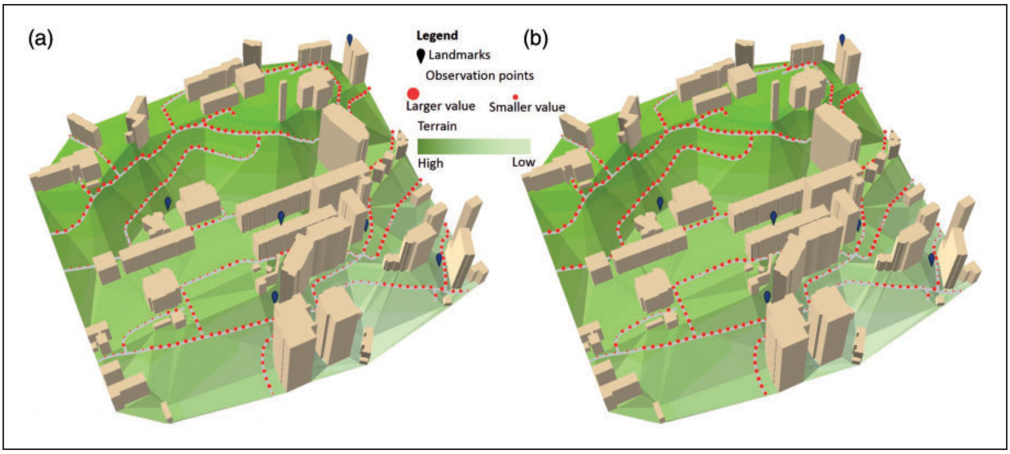

Figure 5. (a) The targeted connectivity to landmarks for a campus with six statuses acting as targets; this represents the number of visible statuses. (b) The targeted integration refers to the normalized value of the sum of the shortest path distance (based on visibility relations) from an observation point to all other targets in the graph.

the lower part. Those two values were closely correlated (r=0.72, p<0.01), albeit with notable differences in some locations.

Discussion

Theoretical contributions

Our novel approach to using visibility graphs in 3D spatial systems makes two contributions to theory.

(1) Graph-based visibility analysis, developed from space syntax and social network theory (Turner et al., 2001), embraces mutual visibility between locations. However, methodological constraints limit its application in 2D spaces. To allow the use of visibility graphs in 3D environments, manually linking visibility lines between different floors is a possible workaround. However, this workaround is tedious and prone to errors, and it cannot deal with complex 3D systems such as House NA. Other studies have explored various properties or presentations of individual 3D isovists, such as the volume of open spaces, areas, or visible sky in a GIS platform. However, graph-based 3D visibility analysis has not previously been directly explored.

We propose that any 3D system can be tessellated into a 3D grid of points with equal distance (along the x, y, z axes). A graph for a 3D system can be constructed by using isovist-generating locations as nodes and visibility relationships between those nodes as edges in the GIS platform. This approach can handle any complex 3D built environment, such as multilevel atrium buildings or urban spaces with canopy or overpass bridges.

(2) Furthermore, we draw a distinction between a *generic visibility graph* and a *targeted visibility graph*. In the *generic visibility graph*, only occupiable locations—the set of spaces that people can physically occupy—are regarded as nodes in the graph. The mutual visibility between these occupiable locations forms the edges in this

graph. This approach bears a strong resemblance to the original 2D *visibility graph analysis*, although it is applicable to 3D environments.

In the *targeted visibility graph*, we further take into account the visible spaces or specific targets in a system. Visible locations are spaces people can see but cannot necessarily access. Only the visibility relations between two occupiable locations and that from one occupiable to one visible location or target form the edges of the graph.

In essence, visible locations can be considered a special form of target in a system. Varoudis and Psarra (2014) also developed 3D visibility graphs in Sketchup. Technically similar to ours, their proposal involves a mixed graph of "directed" and "undirected" visual connections as edges to differentiate occupiable locations from visible locations. However, our *targeted visibility analysis* departs from theirs by extending the support for other forms of targets besides visible location. For example, patient bed may have greater cognitive impact on caregivers in an intensive care unit, and thus may deserve to be the focus of an analytic visibility model (Lu, 2010). As Gibson suggested, people are sensitive and can directly perceive functionally significant properties of an environment as a "value-rich ecological object" (Gibson, 1979: 140). Therefore, a *targeted visibility graph* focusing on silent targets in a spatial system may better explain people's spatial understanding and spatial behavior compared to the *generic visibility graph* or Varoudis and Psarra's approach.

By separating occupiable locations and visible locations or targets, we have made the graph system more amenable to new applications in 3D architectural and urban design, while retaining a mapping back to the original 2D *visibility graph* methods through the *generic visibility graph*. We have proposed three measures of the graph in terms of its spatial relationship to others, which may be useful for investigating human understanding and behavior in architectural and urban spaces. The measure of *targeted connectivity* and *targeted connectivity index* are two local measures of the graph because they depend only on the nodes in a neighborhood, whereas the *targeted integration* is a global measure because it depends on the relative graph-based path distance to all other nodes in the graph.

Future research directions for new insights

Our four examples illustrate that the 3D visibility graph opens doors to investigating a variety of research situations, ranging from objectively describing the spatial properties of complex architectural design to explaining human understanding and behavior in 3D spaces.

The example of T-shaped geometry demonstrates that the measures of 3D visibility graphs are sensitive to the change of z-dimension and reveal 3D spatial characteristics. It indicates that our approach surpasses 2D visibility graph analysis, which cannot distinguish systems with variation only along the z-dimension.

The case of House NA further shows that the 3D visibility graph can objectively describe and compare a location's visual accessibility to that of other locations in a complex 3D system. It is more important given that architects often accentuate the 3D visual interconnections among different spaces by expanding the visual fields in a 3D way, such as by providing openings, atriums, transparent partitions, or courtyards. The strong association between an architect's allocation of rooms with different levels of required privacy in House NA and the objectively measured visual accessibility from our model confirms that the architect has been acutely conscious of the visibility patterns within this complex spatial system. Our approach and related measures may have direct application in describing and assessing the visual properties of architectural design works.

Recently, the question of wayfinding behavior in multilevel buildings has become central to architectural and environmental psychology studies (Holscher et al., 2006; Hölscher et al., 2012; Jeffery et al., 2013; Thibault et al., 2013). It is still unclear how people memorize 3D spaces or how 3D spatial configuration affects their wayfinding behavior. Research in such areas could benefit from description systems that capture behaviorally and psychologically relevant properties of space (Zimring and Dalton, 2003). Therefore, our analytic model may pave the way for further studies of wayfinding and spatial cognition in multilevel buildings, as shown in the third example of the shopping mall. Furthermore, the *targeted visibility graph analysis* can focus on a set of salient targets in a system, which is beyond the capability of Varoudis and Psarra's approach (Varoudis and Psarra, 2014). The *targeted 3D visibility graph* also has direct design implications. For example, we can compare the visibility of different targets in a system, evaluate different design alternatives, or identify the location where a target has the maximum visibility impact.

In addition to 3D buildings, 3D *visibility graph analysis* could also be used to analyze urban-scale environments. As shown in the fourth example, our analytical model has potential broad application in urban settings because our tool was developed in ArcGIS (ESRI, CA, USA). It is seamlessly integrated with a wide range of spatial data—terrain, streets, building footprints and height, or 3D urban models—available from government agencies or other resources. Our GIS-based approach has the edge over Varoudis and Psarra's approach in terms of data support, integration, and visualization.

Conclusion

This study is an effort to explore a new analytical approach of visibility graph analysis in 3D space. As shown in the four empirical examples, this new approach works better than existing 2D or 3D visibility graph analysis. It may help designers and researchers explore the visibility and permeability relations or spatial cognition and behavior in a complex 3D system. The tool and related measures may assist urban designers and architects to achieve in-depth understanding of 3D built environments and the associated behavioral or cognitive impacts.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The work described in this paper was fully supported by the grants from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. CityU11612615 & CityU11666716) and National Natural Science Foundation of China (Project No.51578474).

Note

1. The 3D visibility graph extension for ArcGIS 10 can be downloaded from the following link. www.researchgate.net/publication/318561612_3D_visibility_graph

References

Batty M (2001) Exploring isovist fields: Space and shape in architectural and urban morphology. *Environment and Planning B-Planning & Design* 28: 123–150.

Benedikt ML (1979) To take hold of space – Isovists and isovist fields. *Environment and Planning B-Planning & Design* 6: 47–65.

Chamberlain BC and Meitner MJ (2013) A route-based visibility analysis for landscape management. *Landscape and Urban Planning* 111: 13–24.

Choi YK (1999) The morphology of exploration and encounter in museum layouts. *Environment and Planning B-Planning & Design* 26: 241–250.

Churchill A, Dada E, de Barros AG, et al. (2008) Quantifying and validating measures of airport terminal wayfinding. *Journal of Air Transport Management* 14: 151–158.

Dalton R and Dalton N (2015) The problem of representation of 3D isovists. In: Karimi K, Vaughan L, Sailer K, et al. (eds) *The 10th International Space Syntax Symposium*. London: UCL.

Fisher-Gewirtzman D (2015) Is perception quantifiable? Combining measurements of space with quality of the view. In: *Third annual international conference on Architecture and Civil Engineering (ACE 2015)*, Singapore.

Fisher-Gewirtzman D (2016) Integrating 'weighted views' to quantitative 3D visibility analysis as a predictive tool for perception of space. *Environment and Planning B: Urban Analytics and City Science*. Epub ahead of print. DOI: 10.1177/0265813516676486

Fisher-Gewirtzman D, Burt M and Tzamir Y (2003) A 3-D visual method for comparative evaluation of dense built-up environments. *Environment and Planning B-Planning & Design* 30: 575–587.

Fisher-Gewirtzman D, Shach Pinsly D, Wagner IA, et al. (2005) View-oriented three-dimensional visual analysis models for the urban environment. *URBAN DESIGN International* 10: 23–37.

Frearson Aa (2012) *House NA by Sou Fujimoto Architects*. Available at: www.dezeen.com/2012/05/08/house-na-by-sou-fujimoto-architects/.

Gibson JJ (1979) *The Ecological Approach to Visual Perception*. Mahwah, NJ: Lawrence Erlbaum Associates Inc, US.

Haq S and Zimring C (2003) Just down the road a piece. *Environment and Behavior* 35: 132–160.

Hillier B and Hanson J (1984) *The Social Logic of Space*. Cambridge: Cambridge University Press.

Hillier B and Tzortzi K (2006) Space syntax: The language of museum space. In: Macdonald S (ed.) *A Companion to Museum Studies*. UK: Blackwell, pp. 282–301.

Hölscher C, Brösamle M and Vrachliotis G (2012) Challenges in multilevel wayfinding: A case study with the space syntax technique. *Environment and Planning B: Planning and Design* 39: 63–82.

Holscher C, Mellinger T, Vrachliotis G, et al. (2006) Up the down staircase: Wayfinding strategies in multi-level buildings. *Journal of Environmental Psychology* 26: 284–299.

Jeffery KJ, Jovalekic A, Verriotis M, et al. (2013) A framework for three-dimensional navigation research. *Behavioral and Brain Sciences* 36: 571–587.

Koltsova A, Tunçer B and Schmitt G (2013) Visibility analysis for 3D urban environments. Research development and practical application. In: Stouffs R and Sariyildiz S (eds) *Models of Computation: Human Factors – Volume 2 – Computation and Performance – eCAADe 31*. Delft, The Netherlands: Faculty of Architecture, Delft University of Technology, p. 375.

Lam WHK, Tam ML, Wong SC, et al. (2003) Wayfinding in the passenger terminal of Hong Kong International Airport. *Journal of Air Transport Management* 9: 73–81.

Lu Y (2010) Measuring the structure of visual fields in nursing units. *Herd: Health Environments Research & Design Journal* 3: 48–59.

Lu Y and Peponis J (2014) Exhibition visitors are sensitive to patterns of display covisibility. *Environment and Planning B: Planning and Design* 41: 53–68.

Lu Y and Seo HB (2015) Developing visibility analysis for a retail store: A pilot study in a bookstore. *Environment and Planning B: Planning and Design* 42: 95–109.

Lu Y and Ye Y (2017) Can people memorize multilevel building as volumetric map? A study of multilevel atrium building. *Environment and Planning B: Urban Analytics and City Science*. Epub ahead of print. DOI: 10.1177/2399808317705659

Lu Y and Zimring C (2012) Can intensive care staff see their patients? An improved visibility analysis methodology. *Environment and Behavior* 44: 861–876.

Morello E and Ratti C (2009) A digital image of the city: 3D isovists in Lynch's urban analysis. *Environment and Planning B: Planning & Design* 36: 837–853.

Newhouse V (2005) *Art and the Power of Placement*. Broadway: The Monacelli Press.

Omer I and Goldblatt R (2007) The implications of inter-visibility between landmarks on wayfinding performance: An investigation using a virtual urban environment. *Computers, Environment and Urban Systems* 31: 520–534.

Peponis J, Dalton RC, Wineman J, et al. (2004) Measuring the effects of layout upon visitors' spatial behaviors in open plan exhibition settings. *Environment and Planning B-Planning & Design* 31: 453–473.

Psarra S (2005) Spatial culture, way-finding and the educational message: The impact of layout on the spatial, social and educational experiences of visitors to museums and galleries. In: MacLeod S (ed.) *Reshaping Museum Space*. London & New York: Taylor & Francis, pp. 78–94.

Psarra S (2009) *Architecture and Narrative: The Formation of Space and Cultural Meaning*. London & New York: Routledge.

Shach-Pinsly D, Fisher-Gewirtzman D and Burt M (2006) A quantitative method for visual analysis: A comparative evaluation for urban coastal environments. *Journal of Architectural and Planning Research* 23: 305–327.

Stamps AE (2005) Isovists, enclosure, and permeability theory. *Environment and Planning B-Planning & Design* 32: 735–762.

Suleiman W, Joliveau T and Favier E (2013) A new algorithm for 3D isovists. In: Timpf S and Laube P (eds) *15th international symposium on spatial data handling – Geospatial dynamics, geosimulation and exploratory visualization*. Berlin Heidelberg: Springer-Verlag, pp. 157–173.

Thibault G, Pasqualotto A, Vidal M, et al. (2013) How does horizontal and vertical navigation influence spatial memory of multifloored environments? *Attention, Perception, and Psychophysics* 75: 10–15.

Turner A, Doxa M, O'Sullivan D, et al. (2001) From isovists to visibility graphs: A methodology for the analysis of architectural space. *Environment and Planning B-Planning & Design* 28: 103–121.

Tzortzi K (2004) Building and exhibition layout: Sainsbury Wing compared with Castelvecchio. *Architectural Research Quarterly* 8: 128–140.

Varoudis T and Psarra S (2014) Beyond two dimensions: Architecture through three-dimensional visibility graph analysis. *The Journal of Space Syntax* 5: 91–108.

Watts DJ and Strogatz SH (1998) Collective dynamics of 'small-world' networks. *Nature* 393: 440–442.

Yang PPJ, Putra SY and Li W (2007) Viewsphere: A GIS-based 3D visibility analysis for urban design evaluation. *Environment and Planning B: Planning and Design* 34: 971–992.

Zamani P and Peponis J (2010) Co-visibility and pedagogy: Innovation and challenge at the High Museum of Art. *The Journal of Architecture* 15: 853–879.

Zimring C and Dalton RC (2003) Linking objective measures of space to cognition and action. *Environment and Behavior* 35: 3–16.

Yi Lu is an Assistant Professor in the Department of Architecture and Civil Engineering at City University of Hong Kong, Hong Kong SAR, China. His research areas include spatial analysis, environment and behavior studies, and healthy built environment.

Zhonghua Gou is a Lecturer in the School of Environment at Griffith University, Australia. His research areas include evidence-based design, and architectural science.

Yu Ye is an Assistant Professor in the Department of Architecture at Tongji University, Shanghai, China. His research areas include urban design, urban morphology, and big data.

Qiang Sheng is an Associate Professor in the School of Architecture and Design at Beijing Jiaotong University, Beijing, China. His research areas include space syntax and pedestrian movement.