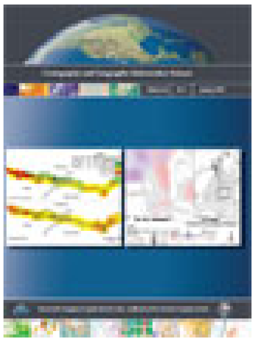

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Unpacking isovists: a framework for 3D spatial visibility analysis

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ABSTRACT
This article explores the ways in which researchers conceptualize and visualize visibility in spatial research – using isovists and visualscapes. We review how visibility analyses have been used in spatial analysis and visualization. We dissect the geometric conceptualization of isovists, and geometric relationships between isovist origins and targets. From this, we develop an expanded typology of isovists based on geometries of visibility and the relationships between an observer and the observed. This typology differentiates panoptic isovists, constrained isovists, and targeted isovists. We apply these isovist examples to urban privacy and surveillance to ground the new conceptual framework. We conclude with a discussion surrounding future research and conceptual development needed to advance visualscapes and visibility analysis.

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Isovists; visibility; visualscapes

Introduction: visibility and viewshed analysis

Visibility analysis, through the use of geographic information systems (GISs), computes and analyzes the visibility of objects and space. The visualscape was introduced in an attempt to unify methodological approaches to visibility analysis within geographic information science (GIScience). This concept is defined as a "spatial representation of any visual property generated by, or associated with, a spatial configuration" (Llobera 2003, 30). Visualscapes encompass analytical techniques such as intervisibility, viewsheds, isovists, and visibility graphs.

The most ubiquitous GIS platforms perform viewshed analyses using: (i) vector ray tracing; and (ii) raster algorithms designed to interpret elevation coordinates attached to a particular set of X and Y coordinates. Various forms of visualscapes can be generated in this manner. For example, intervisibility considers whether one point can be seen from another (Longley 2011), whereas a viewshed considers the area of the surface that is visible from a point location. Viewsheds can be applied to a variety of spatial relationships and phenomena including: determining what is visible from a tourist viewpoint, the visual impact of new constructions, and optimal logging sites for natural vista preservation. Additionally, the viewshed approach can be extended to other line of sight (LOS) spatial relationships such as solar radiation exposure and cellular transmission strength.

The isovist is a popular technique used in a variety of fields to compute visibility. Originally conceptualized by Tandy (1967), the isovist is defined as the volume of space representing the visual field of an observer from a specified origin (Benedikt 1979). Isovist research has typically used a panoptic approach in the generation of isovists and resultant visualscapes. We consider 'panoptic' to refer to omnidirectional visibility. While omnidirectional visibility is useful for visualizing potential viewing directions of various entities, it often does not reflect real-world observers, each with varying needs and limitations (people; cameras; lookouts).

In the following sections, we review how visibility analyses have been used in spatial analysis and visualization. We dissect the geometrical relationships of isovist origins, facilitating the development of an expanded isovist typology. Included is the differentiation between panoptic isovists, constrained isovists, and targeted isovists. We unpack the geometric conceptualization of isovists in order to develop a more specific typology of isovists based on geometries of visibility and the relationships between an observer and the observed. The applied examples are used to ground this conceptual framework. We conclude with a discussion surrounding future research and conceptual development needed to advance visualscapes and visibility analysis.

Previous research in visibility analysis

The visualization of visibility (both objects and environment) has been a topic of research for many decades and spans several distinct fields of research. Broad

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types of visibility analysis crop up in a wide variety of problem contexts including national security (VanHorn and Mosurinjohn 2010), healthcare (Alalouch and Aspinall 2007), and navigation (Delikostidis et al. 2013). Patterns of specialized visibility analyses and the resultant visualscapes can be seen across different research domains. The majority of cutting-edge isovist work, for example, has occurred within archeology (Paliou 2011) and urban design (Benedikt 1979; Batty 2001; Fisher-Gewirtzman and Wagner 2003; Turner et al. 2001).

A variety of visibility metrics have been developed in order to analyze and visualize different characteristics of visible space and patterns found within them. These include binary viewsheds (Shultz and Schmitz 2008; Wilson, Lindsey, and Liu 2008), visual openness (Fisher-Gewirtzman and Wagner 2003; Wilson, Lindsey, and Liu 2008), and visual magnitude (Llobera 2003; VanHorn and Mosurinjohn 2010; Wilson, Lindsey, and Liu 2008). These metrics represent distinct quantifiable properties of visibility in differing spatial configurations.

Visibility metric analysis and visualscapes can vary in dimensionality. One of the characteristics of the visualscape, as defined by Llobera (2003), is that they are "essentially three-dimensional [and] they may be explored using any of the standard concepts that apply to 3D surfaces" (31). This suggests that the visualscape embraces a limited form of 3-dimensionality; however, early GIS work was limited by the fundamental structure of 2.5D digital elevation models (DEM) (Bishop 2003). 2.5D structures only account for one elevation value at each XY coordinate. Overhanging geometry, tunnels, and other bridge-like features are not satisfactorily represented in such an approach (Yang, Putra, and Li 2007). Pyysalo, Oksanen, and Sarjakoski (2009) reviewed the differences in LOS viewshed analyses applied to truly 3D voxel representations of the environment and 2.5D DEM representations.

For example, while Wilson, Lindsey, and Liu (2008) converted a 3D LiDAR dataset to a 2.5D elevation model in order to run a visual magnitude assessment, the final visualscapes are presented in 2D. VanHorn and Mosurinjohn's (2010) study on sniper hazards used the extrusion of a 2.5D raster array to represent urban topography. This contrasts with their topologically 3D approach to hazard visualization, which placed a spherical 3D weapon potential dome within their study area. Given our increasing capability to run sophisticated 3D analysis, misrepresentation of analytical processes and results is a real risk.

Isovist research has fully embraced, and responded to, this challenge. In particular, the field of urban design has produced sophisticated prototypes, tools, and metrics, and other conceptual research. Conceptual constructs that utilize isovists include isovist fields and spatial openness. Other properties such as isovist openness and jaggedness have shown promise as predictors of spatial behavior and experience (Wiener and Franz, 2005).

Isovist fields are generated by generating isovists at regular intervals within a defined space, then using the results to produce a field representing sum attributes of the generated isovists (Benedikt 1979; Batty 2001; Turner et al. 2001). Attributes represented by the fields can include metrics such as isovist area and perimeter. These methods are stated to be applicable in 3D (Turner et al. 2001), but were neither fully developed nor tested until (Teller 2003).

Fisher-Gewirtzman and Wagner (2003) reported on the conceptual development and application of spatial openness. Spatial openness is "the volume of free space measured from all internal observation points," (37) or in other words, isovist volume. In this work, the authors are restricted to 2D isovist area (Turner 2003); however, recent development demonstrates a successful shift to truly 3D analysis using 3D voxel representations of the environment (Fisher-Gewirtzman 2012; Fisher-Gewirtzman, Shashkov, and Doytsher 2013).

An expanded isovist typology

The application of 3D isovists in spatially complex environments necessitates the development of a more robust isovist typology than that which currently exists. We propose a classification framework with which we can specify a typology of isovist attributes: isovist-target relationships, intervisibility, isovist interception, isovist mobility, and scanning versus fixed isovist behavior. Through this framework, we aim to deliver a conceptual basis with which to compare and evaluate the implications of using one or more isovist-based visibility analyses in different analytical contexts. We ground this typology with existing examples of isovist use in the literature and expand were none yet exist. A richer conceptual framework for isovists enables us to design visibility analyses for unique geometries of specific problem contexts.

Unpacking the geometry of panoptic and constrained isovists

Most isovist applications employ what we have defined in section 'Introduction: visibility and viewshed analysis' as panoptic isovists. New research has unlocked the capability to generate and analyze 3D isovists; with these new opportunities demanding for clearer terminology when both subtle and drastic variations of visibility origin geometry are present. Targeted isovists and constrained isovists are distinguished from the panoptic isovist in this new lexicon. These differentiations must be explicitly acknowledged (and perhaps dealt with).

Our conceptualization of the panoptic isovist is derived from Jeremy Bentham's panopticon (Bentham 1995; Foucault 1995). Bentham's theoretical prison contains a guard tower that is capable of viewing in all directions at once; likewise, the panoptic isovist is generated from an origin point with an omnidirectional gaze (Figure 1(a) and (b)).

Examples of panoptic isovists are very common and are present in both 2.5D and 3D visibility analyses. Fisher-Gewirtzman (2012) considered visibility from all angles without restriction in their topologically 3D approach to assessing spatial openness. Likewise, Wilson, Lindsey, and Liu (2008) do not restrict the viewing potential of their viewshed origins in their topologically 2.5D examination of visual openness and magnitude for urban pedestrian trails. It must be noted that this is not implicitly a criticism of their approach. Panoptic isovists are extremely useful for assessing the potential viewshed of an observer at a fixed location. That being the case, no human can observe in 360° at once. As such, the use of panoptic isovist necessitates that any result generated reveals potential visibility (however, an exception might be made for two or more observers standing back-to-back, or a complex closed-circuit television (CCTV) set-up). Such an approach reveals what an observer could see, not what they will or do see.

There are fewer examples of restricted isovists being applied in the literature. Paliou (2011) incorporated the maximum vertical eye rotation limitations in their analysis of Bronze Age mural visibility. The author in this case did not choose to limit the visibility in the

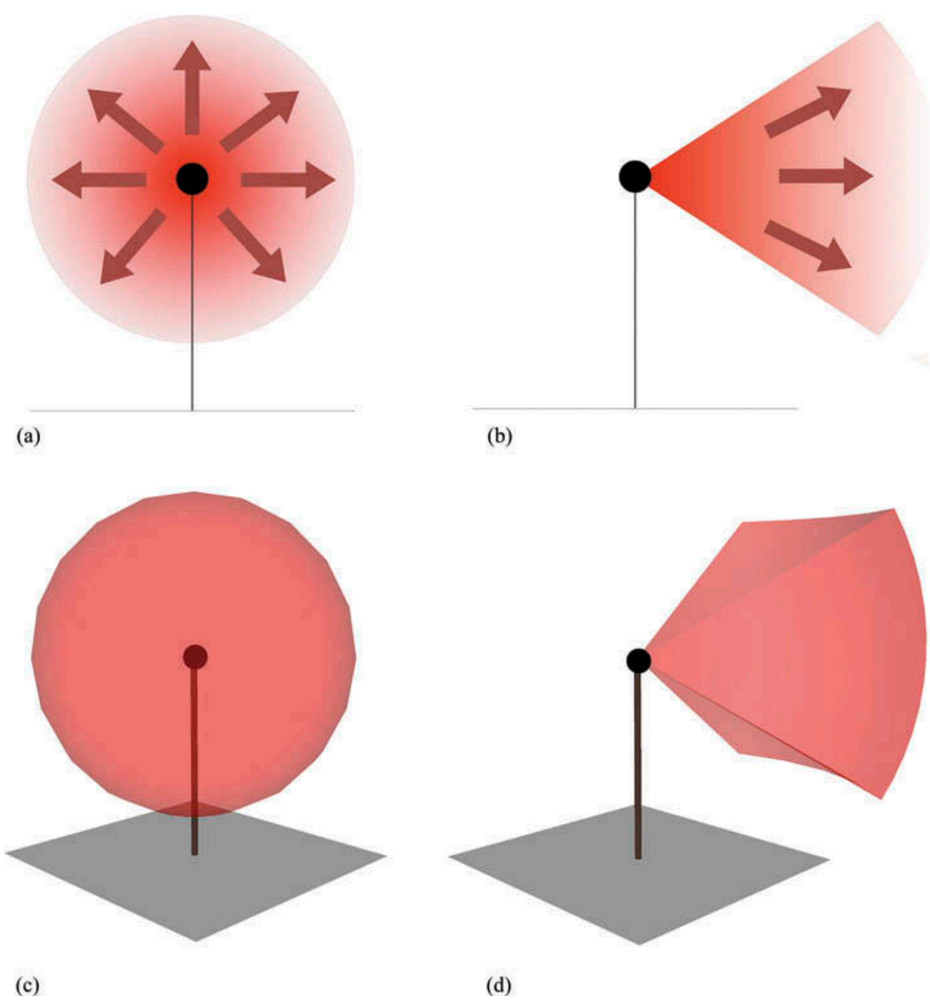


Figure 1. 2D and 3D perspective views of panoptic and constrained isovists. The panoptic isovist (a) and (c) assumes the capability to view in all directions and at all angles from an origin. The constrained isovist (b) and (d) has some form of limited observational capabilities. This may include limited viewing angles and directionality.

horizontal view; as a result, the article still represents potential visibility. Again, it is important to note that this is not an implicit criticism, but we feel that the relationship between the geometry of the isovist and resultant visibility representations must be made clear. Choices made in how we structure visibility affects what final visualscapes represent.

In response, we introduce the term constrained isovist to describe isovists generated from viewpoints containing limiting characteristics, such as a limited field-of-view or directionality. Its geometry is variable, but can be likened to a searchlight shining a beam onto a landscape (Figure 1(c) and (d)). This beam has directionality and breadth, which define how much of the landscape is illuminated. Unlike panoptic isovists, the constrained isovist can be used to represent observational constraints.

The application of constrained isovists may be advantageous in situations where an actor has a constrained or focused gaze. For example, constrained isovists would better represent fixed location CCTV cameras with limited fields of view and static directionality. They may also represent observers who can theoretically view any angle or direction, but can only observe a certain range at any given moment.

Considerations of the geometry of isovist origins

We have discussed the differentiation of panoptic and constrained isovists in response to representational issues identified above; however, we have not (yet) taken issue with the representation of observers as fixed points in 3D space. Motivations for computing visibility vary. Many visibility analyses compute isovists from points, which are used as analogs for the origin of optics of a camera or human viewpoint. We propose that isovist origins can be linear, areal, or volumetric. Considering this potential will at the very least enable a healthy discussion on representing observation and visibility, but may also unlock new approaches to visualizing visibility.

As an example, linear origins might be used to compute visibility from a path. Both Conroy and Dalton (2001) and Koltsova, Tunçer, and Schmitt (2013) dealt with path representation by establishing point-origin isovists at regular intervals along a defined route. While this enables sophisticated analysis such as route vision profiles and isovist field generation, they still represent a non-point feature as a series of points. By representing observers as non-point geometries, we present a distinct representational approach. We discuss the merits and disadvantages of such methods at length in section 'Isovist origins and their influence on isovist geometry'.

Areal origins may offer another distinct way to represent visibility and observation. If one were to compute the visibility of a proposed development from viewpoints in an existing town square, computing visibility from each mobile individual human origin within the square would be difficult, somewhat arbitrary, and inefficient. Typically, this is dealt with achieved by generating a lattice of point-origin isovists and developing isovist fields from the results. An alternative approach might be to compute the potential visibility from a polygon representing the town square, at an average head height; this polygon would be an areal origin of an isovist analysis. Areal origins might also be applied in a visual impact assessment of billboards for several reasons: a billboard surface is a 2D polygon, is meant to be viewed from many angles, and the audience must perceive the whole surface at once. This is a distinct approach to representing the geometry of observation when compared with the standard lattice-like analysis of multiple point origins.

Figure 2 illustrates the geometry resulting from panoptic isovists with point, line, and volumetric origins. This differentiation subsequently helps us understand the origin-target relationships between isovist origins and targets of different geometric combinations (Table 1). We propose that by selecting non-point origin geometries, we may represent a conceptually district version of visibility. We discuss these conceptual differences, their advantages, and their disadvantages, and their potential usefulness in section 'Isovist origins and their influence on isovist geometry'.

Isovist interception in applied contexts

Panoptic and constrained isovists are each defined by attributes that exist independent of the environment in which they are computed (observer attributes). Additional properties become relevant when isovists are applied in real spaces. Isovist *range*, as an example, can be considered to be the sensing range of a sensor, or the intended capture range of a system. Distance in the context of isovists has been examined before. Kim and Jung (2014) proposed a distance-weighted isovist field, given the importance of proximity across various spatial disciplines. Many research efforts select maximum distances for isovist limitation. For example, Van Bilsen and Poelman (2009) selected a panoptic isovist with a maximum range of 225 m. The representation of observation is thus a sphere with a radius of 225 m. Scenarios in which the range is relevant might include

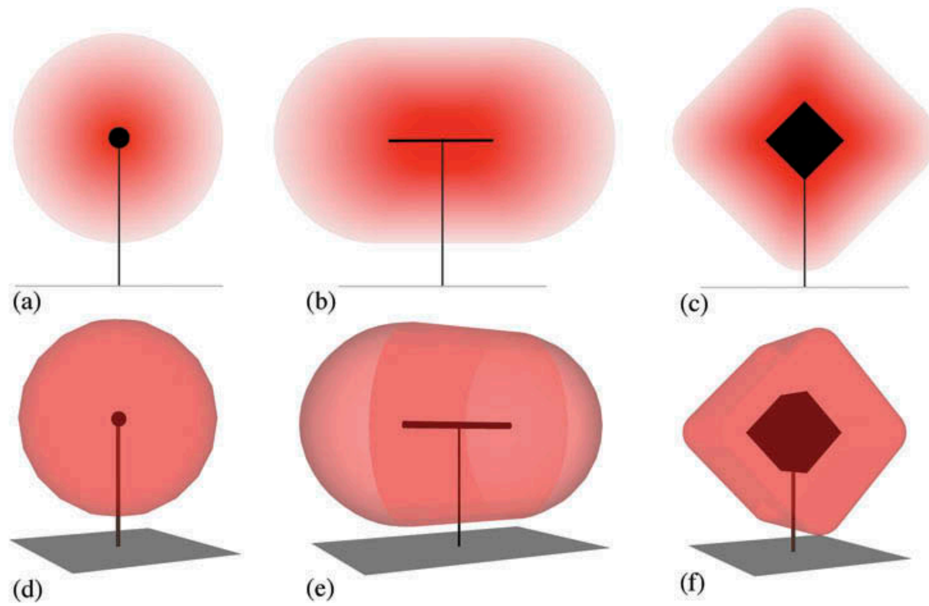


Figure 2. 2D illustrations of the side profile of panoptic isovists with point (a), linear (b) and volumetric (c) origins, and their 3D counterparts (d), (e), and (f).

Table 1. Proposed targeted isovist classifications.

	Target geometry			
Origin geometry	Point	Line	Area	Volume
Point	Point-to-point	Point-to-line	Point-to-area	Point-to-volume
Line	Line-to-point	Line-to-line	Line-to-area	Line-to-volume
Area	Area-to-point	Area-to-line	Area-to-area	Area-to-volume
Volume	Volume-to-point	Volume-to-line	Volume-to-area	Volume-to-volume

the maximum acceptable range of a sensor system or cellular signal propagation.

In certain contexts, *uninterrupted* isovist geometries (of varying ranges) are appropriate representations of visibility phenomena. For example, an isovist generated by an infrared or X-ray camera may pass through solid objects. A panoptic isovist would remain spherical, no matter how the spatial configuration of the environment is changed. In conjunction with the range, sensing wavelength becomes important in determining the final geometry of an isovist in wavelengths that interact with material objects. It is also important to remember that the question of transparency also relates to variable occlusion by objects, such as diffraction and fading linked to the presence of objects with blur limits (e.g. trees).

Whether panoptic or constrained, an isovist will be intercepted by materials that fall within its field of view and range (Figure 3). For example, the cylindrical geometry of Bentham's (1995) panopticon results from the interception of the isovist of surveillance contained within the geometry of the prison building. Understanding these principles and their resultant geometries may help to better understand visibility analyses from a 3D isovist perspective.

Targeted isovists and origin-to-target isovist relationships

In addition to differentiating panoptic and constrained isovists, a more specific terminology might be used to describe 3D visibility relationships between observers and what is observed. We propose the term *targeted isovist* to define a visualscape in which the rendered isovist geometry is limited by a specified target space. The key difference between this and panoptic or constrained isovists is that a targeted isovist does not visualize all that the viewer can see, rather, it reveals only the visible portions of a target space and the gaze path between the observer and target space (Figure 4). In other words, targeted isovists are subsets of panoptic and constrained isovists.

To the best of our knowledge, no one has explicitly considered isovist geometries of this type; however, some research does intersect with our conceptual work. Gal and Doytsher (2013) introduce Visible Pyramids as a component of a mass modeling approach to 3D urban visibility. These geometries are defined by a viewpoint and a rectangular visible surface. These shapes are good representations of what we

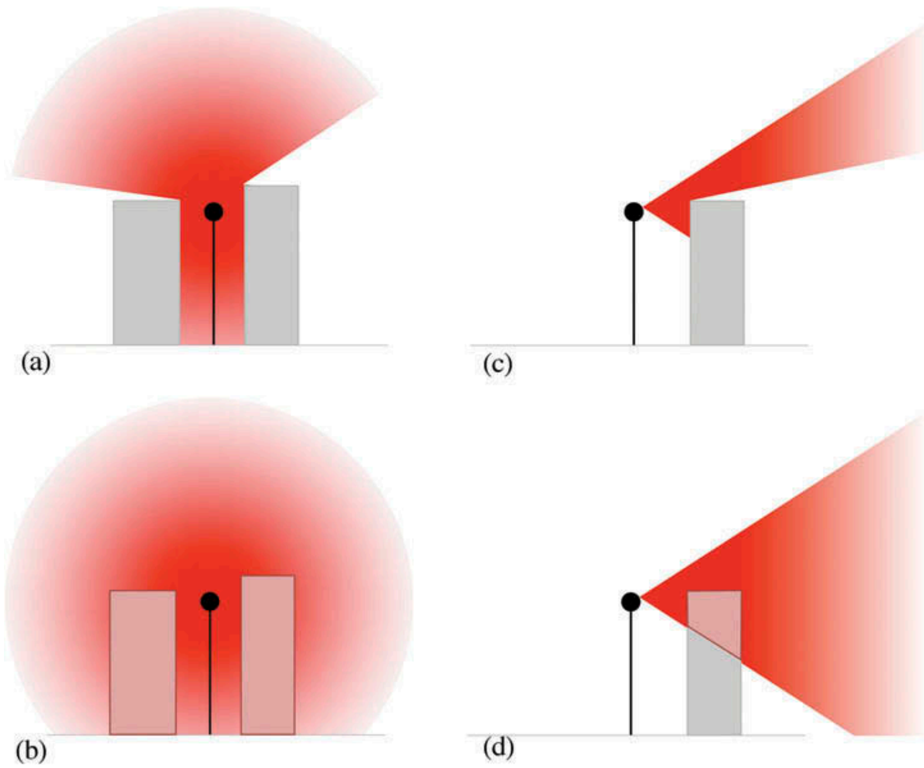


Figure 3. Panoptic (a) and constrained isovists (c) can be interrupted by geometry in certain wavelengths, or remain unimpeded (b) and (d).

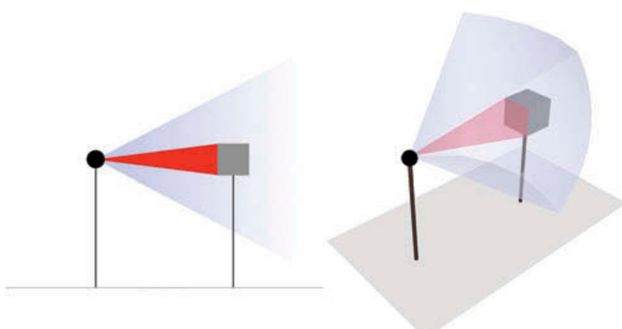


Figure 4. The targeted isovist represents only what is visible of a target area or volume and the gaze path between observer and target. This is a subset of the total viewing capability of the observer, in this case a constrained isovist.

consider targeted isovists; however, they are restricted to pyramidal shapes, something that actual gaze paths might not obey. Paliou (2011) developed an isovist based analysis that reveals the visible area of murals and wall paintings as percentages. These results are visualized as 2D rasters in which visibility can sometimes be seen to project outwards from the targeted features. If one is to consider the paintings to be origins of visibility, the visualscape representing 'high-visibility' sections of space appear to be similar to our targeted isovists conceptualization.

Sub-categories of targeted isovist can be defined using the geometric attributes of both its origin (section 'Considerations of the geometry of isovist origins' above) and target space. This includes points, lines, areas, and volumes. A preliminary categorization of isovist origin-to-target combinations by geometry can be found in Table 1. Figure 5 illustrates some examples of origin-to-target geometric pairings.

This classification might add clarity to real-world visibility contexts. For instance, point-point targeted isovists may be appropriate in determining the best locations for CCTV cameras monitoring a (small) singular object. A continuous line (intervisibility) from the camera to the object must be unbroken in order to maintain security, regardless of the camera's field of view. Point-to-area isovists might describe the visibility of a movie screen from specific seats. Premium seating should be designed so that the entire area of the screen is visible from a viewer's seat. The visibility of anything else (the non-visualized portion of the viewer's total isovist) is irrelevant to the problem at hand. A point-to-volume targeted isovist might define the visibility of the contents of an apartment room from an external viewpoint. The point-to-volume isovist would reveal both the 3D space within the apartment that is visible to the observer, and their gaze path.

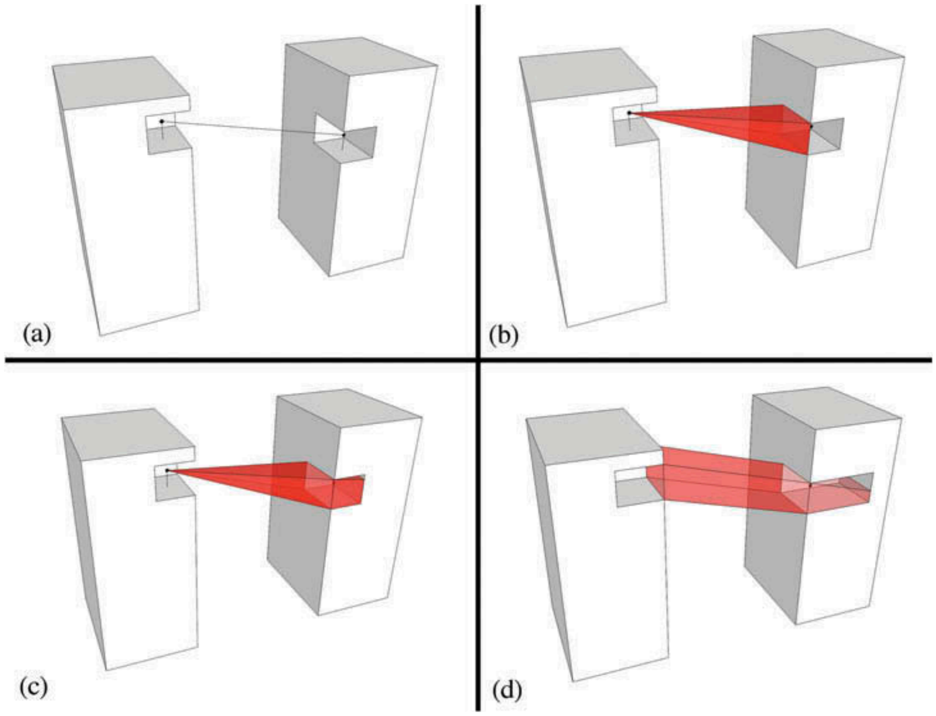


Figure 5. A selection of targeted isovists with differing origin-to-target geometries: (a) point-to-point, (b) point-to-area, (c) point-to-volume, (d) area-to-volume.

We have discussed the possible applications of various point-to-space isovists; however, as discussed in section 'Considerations of the geometry of isovist origins', observer geometries are not necessarily restricted to a single point in space. This can be illustrated by expanding upon our point-to-volume apartment visibility. The apartment room is likely to be visible from several rooms within the opposite building; as such, calculating the room's visibility from a singular point does not reveal realistic visibility. Instead, a volume-to-volume isovist might be more appropriate. Point observers may choose to shift their location within a certain volume in order to peer into the target space. By representing these potential locations of the observer as a volume, a volume-to-volume isovist geometry is produced. This visualizes what can potentially be seen from possible viewpoints.

These examples of variable origin and target geometry suggest that there are a wide variety of key geometrical and conceptual differences in the application of isovists to problem spaces. The selection of different representative geometries often results in critical differences in what the final visualscapes represent. A detailed lexicon and classification system of targeted isovists might be beneficial in the communication of these differences and might stimulate the development of new forms of visibility analysis.

Dynamic isovists and visibility

Many observers are mobile, and are therefore poorly represented by fixed geometries. Early work in dynamic isovists can be seen in Fisher-Gewirtzman, Burt, and Tzamir (2003) where a space-time experience track is visualized as a series of static isovists and a collection of views. The classifications discussed above do not include dynamic attributes such as moving observer locations, changing directionality, and varying viewing angle. This might be engaged by representing mobile point actors as lines, areas, or volumes; however, it forces any resulting visualscapes to represent potential visibility of a mobile observer, rather than the actual visibility of a mobile observer. We address the representation of mobile observers and dynamic isovists without resorting to potential visibility in following sections; however, we first discuss a classification scheme for representing dynamic observers and isovists.

Table 2 gives a preliminary taxonomy for dynamic isovists. Mobile observers with changing physical locations can be classified as mobile or immobile. Examples of mobile observers include moving pedestrians and cars, while stationary CCTV cameras are immobile. Isovists may also exhibit scanning behavior. For example, some security cameras can adjust their orientation, resulting in a greater swath of potential visibility. Finally, an observer may possess zoom and focus

Table 2. Proposed dynamic isovist classifications.

Is the isovist...	Moving?	Scanning?	Focusing?
Yes	Mobile	Scanning	Focusing
No	Immobile	Fixed	Non-focusing

capabilities that change. For instance, a zoom lens alters its total field of view as it is adjusted resulting in isovist geometry that changes through time.

These expanded typologies help us tune visibility analyses to accommodate specific geographic objects, geometries, and spatial relationships. There are many different forms of geometry, mobile actors, and observer-observed relations in the built urban environment. Surveillance and privacy are particularly relevant examples of visibility relationships in urban space. A more sophisticated framework of isovist forms and methods might improve the characterization of these relationships.

An analysis of isovists in two case studies

In the following section, we describe geovisual analysis research we pursued to implement and evaluate selected examples of the isovist and observer-target framework introduced above. Additionally, we seek to conceptualize and implement uncommon isovist geometries (point-to-volume, area-to-area, and volume-to-volume) to enable new forms of visibility analysis.

Two groupings of visualscapes were produced: a 3D targeted isovist privacy analysis of two downtown Vancouver apartment buildings and animated viewsheds along major downtown Vancouver streets. By developing these visualscapes, we evaluate and compare the isovist types, subtypes, geometries, and relationships involved in our conceptual framework designs.

3D isovists and urban privacy

Using urban privacy as an applied context, we demonstrate the potential applicability of both topologically 3D isovists and expanded isovist typologies in order to overcome limitations that arise from traditional approaches to visibility analysis in urban space. Apartment buildings serve as observational platforms that gaze upon and into cityscapes, but may also obstruct (and be obstructed by) urban geometry.

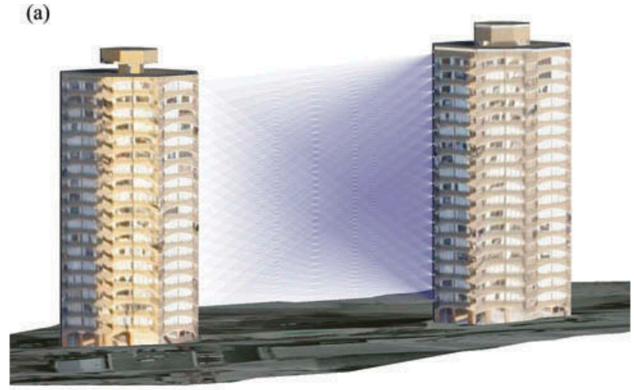
Our research focused upon two Vancouver apartment buildings located at 1616–1666 Pendrell Street. We generated a series of 3D isovists from lines along the faces of each window of each floor. The isovists were generated from horizontal linear origins located 1.5 meters off of the ground at each of the 19 building's floors. This is representative of an observer standing at any point along the window; as such, we represent potential visibility.

Using the conceptual framework of the targeted isovist introduced above, we examined the capability of the isovists to view a volume of space 3 meters deep into the opposing building. Under the targeted isovist classification scheme described in section 4.4, these geometries are defined as line-to-volume targeted isovists. Figure 6(a) reveals the entirety of targeted isovists originating from Building A.

A sample-targeted isovist is shown in Figure 6(b). The volume represents all that can be seen of a specific target area from a certain viewing location and the observer's view-path. Our specified target areas are apartments in Building B. 19 targeted isovists were created per floor for a total of 361 targeted isovists; each one revealing the visibility of a target space within Building B from Building A.

By selecting key isovists for visualization, relative privacy and isovist-origin specific privacy can be revealed. We exposed specific volumes of an apartment and their relative visibility from differing vantage points (the top, middle, and ground floors of

(a)



(b)

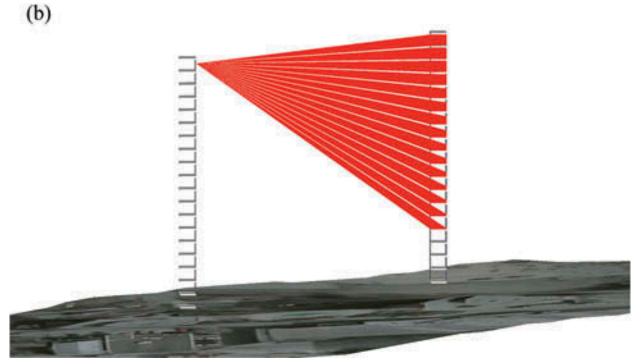


Figure 6. Targeted isovists are projected from the left building (a). Line-to-volume targeted isovists are projected from one building to another (b). The origin of the isovist is a line along the top floor of the left-hand building, while the target volumes are apartments in the right-hand building.

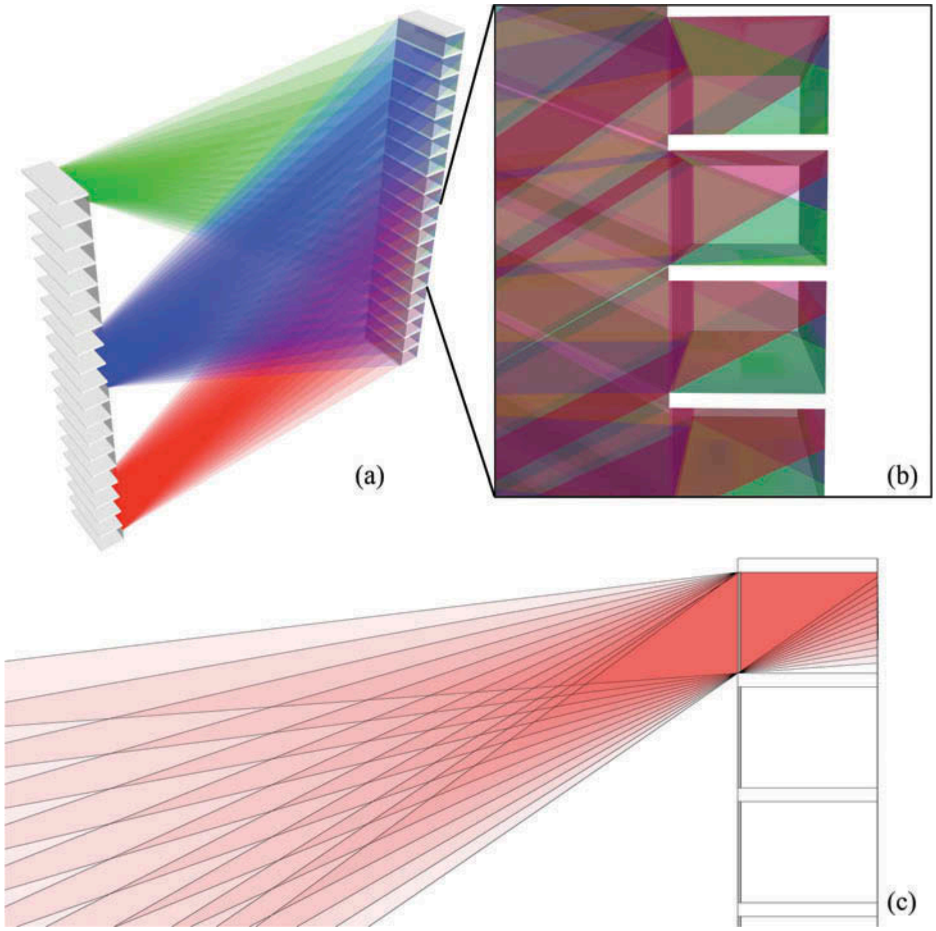


Figure 7. Overlaying multiple targeted isovists (a, b) revealing the relationship between visibility origins, targets, and spatial configurations. Relative privacy of a specific target volume is revealed by visualizing only the targeted isovists that enter a targeted space (c).

Building A). The resulting geometries show visibility from different origins varies throughout the targeted building (Figure 7(a) and (b)).

Relative privacy of target spaces can also be demonstrated. A specific apartment was queried and all of the targeted isovists that breach that volume of space were visualized (Figure 7(c)). This can be considered a topologically 3D cumulative visibility analysis. The accumulation of geometry reveals a pattern; spaces close to the window and ceiling are more visible while space is less visible as one moves into the room and approaches the floor.

As a final exercise, we applied a classification scheme to the building floors in order to represent cumulative visibility and privacy from floor-to-floor. A projection all of the targeted isovists was used to classify each building floor. An isovist was counted if it incurred a privacy violation (defined as an isovist encroaching at least 3 meters into an apartment). These incursions were tallied and a symbology was applied to the 3D model of the apartment building (Figure 8). The least private floors have 17 privacy

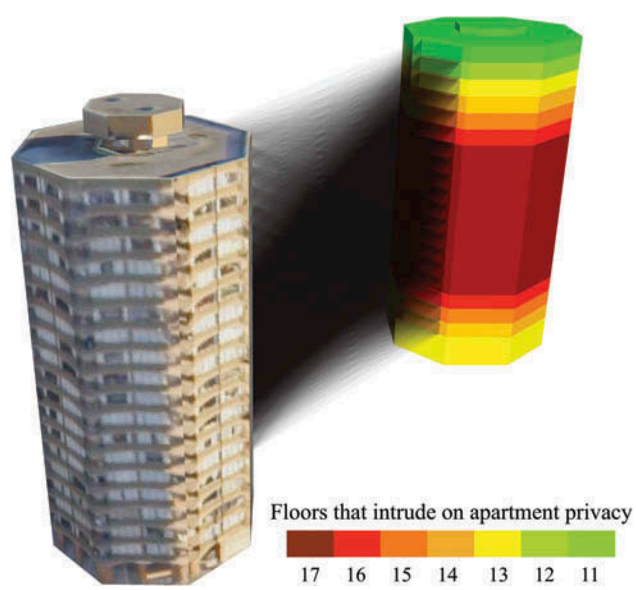


Figure 8. A simple classification scheme applied to the apartment building in order to reveal patterns of privacy. This classification both uses topologically 3D geometry and is based in topological 3D analysis.

incursions, while the most private floors have only 11. The resulting product reveals relative privacy that is not only visualized using the buildings' 3D geometry, but is defined by it.

Dynamic isovists for dynamic observers

We have previously discussed the use of line-, area-, and volume-to-target isovists to reveal potential visibility from mobile observers; however, this does not capture their moment-to-moment dynamism. Static visualscapes do not offer an adequate solution to this problem. In response, we developed 2D animations revealing the mobile isovists of cars along major Vancouver streets with the goal of illustrating the advantages of dynamic isovists and the necessity of a dynamic isovist classification scheme.

We generated 2D isovists at equal intervals along streets within the downtown core of Vancouver using a 2D DEM containing building elevation data. A 2D animation was then developed from this analysis. By animating individual frames in the proper temporal order, the mobile viewshed of a dynamic observer can be visualized (Figure 9). Draping the isovist onto an extruded DEM resulted in an additional (2.5D) visualization. The isovists used in this analysis can be defined as mobile and scanning isovists given our previously discussed classification schemes.

The animations in both 2D and 2.5D capture the dynamic aspect of urban entities in a manner that static visualscapes do not. As the animations progress through time, the isovists shift accordingly. Differences between the 2D and 2.5D visualizations reveal the limitations and advantages of the respective approaches.

The 2D animation does not adequately represent the complex and vertical topography of a downtown core. It is possible to visualize viewsheds on nearly horizontal surfaces; however, the vertical sides of skyscrapers are nearly impossible to see. Only a few cells are illuminated in a top-down view, while in reality the observer should be able to see the entirety of a building's imposing vertical surfaces.

The 2.5D animation improves the communication of visible vertical surfaces; however, it is not perfect. The viewing angle of the visualization has been changed so that building faces can be observed. Users are now able to determine what portion of a particular building face is visible. Additionally, the scale of visual space dominated by the building faces is fully revealed. Downsides to this approach include the occlusion of buildings and building faces that are hidden behind other geometries; however, this problem is not unique, as all 3D visualizations must deal with this limitation in some fashion. It is important to note that analysis of the visibility of vertical facades is a persistent problem for 2.5D isovists in general, and not just ones that are animated.

Discussion

This article offers a framework for a general typology of isovists in two and three dimensions, focusing on the structural relations of observer and observed, in the context of privacy and surveillance. We focused on delineating and quantifying the visibility relationships between observer and target entities. This approach emphasizes the use of a specific observer origin location. We acknowledge that this is distinct from automatic computing approaches to visualscapes (such as Joly et al. 2009) which aim to qualify the content of the general visible space independently of the location of the specific observer. These differences remind us that while observer-target analyses are focused on the (inter)visibility geometry of both origin and target, automated computational observer-less visibility analyses intentionally use panoptic

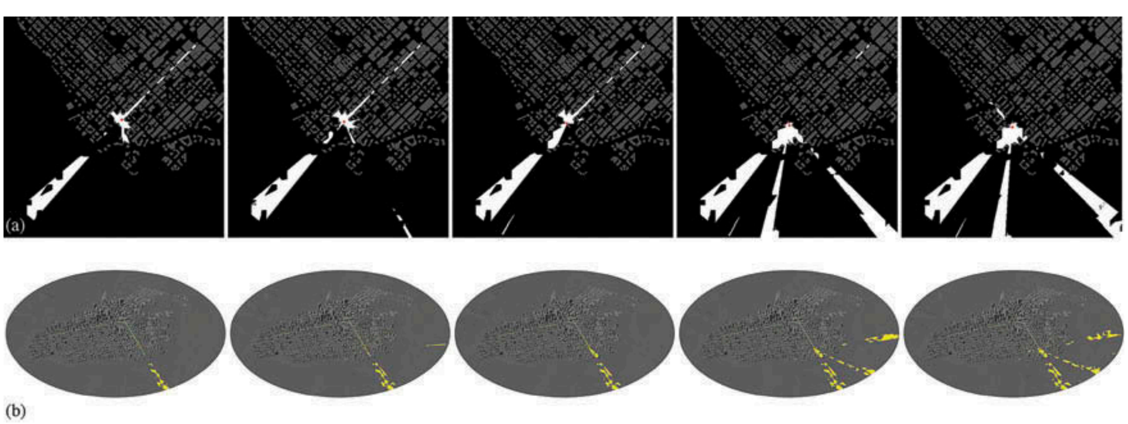


Figure 9. Frames from a 2D (a) and 3D (b) animation revealing the viewshed of a mobile observer in Vancouver's downtown core.

isovists to systematically compute the visual content of an area from any location, and in all directions.

This distinction was brought into focus as our work moved away from point observer origins, and into areal observer-target contexts (such as visibility from within public squares, and of non-point-geometry targets such as digital billboards).

Conceptualizing isovists

Isovist theory and isovist analyses have gained considerable momentum in the spatial analytical literatures. In part 3 above, we considered the way in which isovists are typically conceptualized in spatial analysis. Definitions of isovists include: "the set of all points visible from a given vantage point in space" (Benedikt 1979, 47); "…the visible space from a vantage point…" (Morello and Ratti 2009); and those by Batty (2001) and Turner et al. (2001). In many cases, the isovists used in analysis are implicitly panoptic, and unconstrained; however, the differentiation of constrained isovists from panoptic isovists is important enough to warrant clear distinction.

While exciting and sophisticated 3D isovist research is present in the field of Urban Design (Batty 2001; Conroy and Dalton 2001; Engel and Döllner 2009; Fisher-Gewirtzman 2012; Fisher-Gewirtzman and Wagner 2003; Shach-Pinsly, Fisher-Gewirtzman, and Burt 2011; Turner et al. 2001) 2D isovists dominate contemporary visibility assessments (Bhatia, Chalup, and Ostwald 2012). Often, these constructs are simply referred to as isovists; however, this conflates what is being represented. 2D isovists are subsets of a 3D isovist. Computational restrictions in early years necessitated the use of 2D isovists in lieu of more complex geometries. This restriction has and will likely continue to diminish given advances in computing technologies. While some applications may not require 3D analysis, progress in the conceptualization of 3D versus 2D geographic space and spatial analysis should enable researchers to more specifically qualify the mode and dimensionality of visibility analysis used. We proposed more nuanced specifications of their panoptic versus constrained natures, and their dimensionality.

Isovist origins and their influence on isovist geometry

In the same way that panoptic isovists have tacitly been the default approach to visibility analysis, the majority of visibility analyses have used point geometry for isovist origins. Leveraging Lynch's (1960) specification of urban geometry, Morello and Ratti (2009) presented and discussed methods to compute isovists for urban features. These isovist analyses were perhaps more focused on the geometry of the urban features rather than the geometry of the isovist origins.

There is nothing wrong with the use of point origin isovists *per se*. Given the correspondence between a geometrical point and a singular human observer, or the optical origin of a camera system; however, other isovist origin geometries are possible, and may be more suitable to the geometry of analysis in specific contexts. The result of this approach might be isovist fields that are more representative of the real world. Batty's (2001) conceptualization of isovist fields provides us with some of the foundation for this observation, and with some of the fuel with which to expand our conceptualization of isovist origins and their geometries:

> "Isovists can be defined for every vantage point constituting an environment, and the spatial union of any particular geometrical property defines a particular isovist field." (Batty 2001)

While Lynch (1960) and many people since, have differentiated the geometry of urban features, perhaps we need to apply equal attention to the geometry of isovist origins. *Vantage points* may in fact be *vantage lines, areas* or *voxels*. As Batty (2001) points out, an isovist field results from the spatial union of geometrical properties of each particular case. So perhaps we might respectfully extend this definition by suggesting that:

> isovists can be defined for every combination of origin geometry (the geometry of observation/origin of visibility analysis) and target geometry (i.e. the object/feature of interest); isovist fields resulting from the spatial union of origin and target geometry combinations.

Our proposition reveals other challenges. Benedikt (1979) noted that to quantify a whole configuration, more than a single isovist is required. He suggests the way in which we experience a space is related to the interplay of isovists. This leads him to formulate an *isovist field* of his measurements. Isovist fields are constructs that record "a single isovist property for all locations in a configuration by using contours to plot the way those features vary through space." (Turner et al. 2001, 45)

If isovist fields result from the spatial union of multiple isovists from all possible vantage points, then we must consider how we derive isovist fields. Isovist fields in both 2D and 3D space present a challenge, given that both 2D and 3D space contain an infinite set of possible vantage points. Peponis et al. (1997) draw a comparison with the necessity of sampling points to draw isovists with sampling points for contour maps. If we interpolate an isovist field from a set of discrete set of points along a path, across an area, or from within a volumetric space, where should the origins be? Are informed sample locations better than a regular grid of point isovist origins to generate the isovist field?

Extending the principles introduced by Openshaw's (1984) Modifiable Areal Unit Problem (MAUP) one might find themselves dealing with a Point Isovist Origin to Isovist-Field Interpolation Problem (PIOIFIP)! Should a grid of point origins be used to compute a 3D isovist field, at what sampling resolution should this be done? Cumulative visibility based on 3D and 2.5D isovist analyses typically use a grid of regularly spaced points to serve as the origins of the analysis (Suleiman, Joliveau, and Favier 2011, 2013). Linear, areal, and volumetric isovist origin points can be used to encompass a wider range of possible visibility geometries, while avoiding the pitfalls of arbitrary point origin choice and interpolation; but, this approach does not allow for any form of immediate *cumulative* visibility analysis. It appears a choice between revealing cumulative visibility through isovist fields at the expense of a MAUP-type challenge, or revealing binary visibility at the expense of cumulative analysis must be made. The analytical potential for non-point origin isovists appears to be limited at this time.

3D isovist analysis

The targeted isovist conceptual framework offers a new perspective on privacy visualization and supports a new typology of isovists that can be expanded and improved through further research. For example, varying definitions of privacy might be incorporated into the analysis, using the following factors: penetration of windows, reflectivity of windows, building shape, distance decay and viewing angles.

While several GIS-focused platforms appear to be trending toward a fully functional GIS with the capability to deal with complex 3D geometry and 3D viewsheds, 3D isovists, and other forms of 3D visualscape a persistent issue with 3D isovist analyses is that most mainstream GIS platforms are not yet optimized for this type of analysis. Because of this, 3D modeling software was used to design the 3D isovist geometries in this research. Critical limitations result from the use of this software: complex geometry and sightline projection is not possible, there is very limited cross-compatibility with common GIS platforms, a lack of GIS symbologies, and limited geo-referencing capabilities. GIS must be developed further to fully support a topologically 3D approach to isovist analysis and generation.

Other environments are typically used when dealing with 3D isovists, especially in the field of Urban Design. Koltsova, Tunçer, and Schmitt (2013) presented a tool for analyzing visual pollution by billboards that runs in a Grasshopper for Rhinoceros, parametric environment. Fisher-Gewirtzmann's (2012) most advanced work utilizes Microsoft visual studio 2008 and GKUT (Open GL Utility Toolkit) to analyze and visualize 3D isovists. These tools possess the GIS capabilities; however, given the current widespread use of topologically 2D GIS environments, these 3D tools have not been implemented to their full potential.

Computing animated isovists along paths

Computing static isovists for paths has been associated with visibility analyses along street networks; however, it is not representative of *dynamic* observers such as pedestrians and automobiles. Computing a visibility isovist for a path is certainly possible in 2D or 3D, using a spline as the origin for ray tracing, for example. This static approach would result in an analysis of visibility potential along a path, outside of time. Using the same method to compute visibility for a pedestrian along a path would not match the pedestrian's temporal mobility in space at each spatial coordinate along the path. This suggests a discontinuity between the conceptual/computational construct and the phenomenon for which it has been generated. An adequate representation of visibility for an individual along the path would require a moving isovist origin matching the location and speed of the pedestrian along the path.

The implication of this relationship is an important one. Visibility analyses from paths can create challenging discontinuities between space, time and the phenomena being observed. Being *everywhere* along a path at once (i.e. ray tracing from a spline) is physically impossible for an individual, but may fit evaluation of a surveillance camera visibility/surveillance *potential*.

While a moving isovist may be a better fit for computing visibility for a moving agent, it raises further challenges. An excellent example of this is Google's StreetView system. Google's StreetView data gathering agents move along paths to generate full coverage of views along road networks; but, the very fact that the data gathering system moves along these paths, and stops to capture each panoramic image group tells us that two important things are going on. First, the imagery – while contiguous in appearance once images are stitched into 360 panoramic images – is in fact a discretization of space. Second, because it takes time to travel from each sampling point to the next, there is a time shift between adjacent samples. Scaled to entire surveys, there is considerable time dilation across geographic space.

These considerations are critical to understanding what isovists do (and do not) capture, and what they therefore do (and do not) represent as samples of geographic space and time. Compelling visualization environments often distract us from these considerations.

Extending isovist types: second and third order isovists

Further differentiation and classification of our typologies introduced in section are both possible and are likely to be useful for visualscape analysis. One such extension is language that can encompass the geometries of isovists formed through reflections and refractions.

Traditional isovist analysis assumes Euclidean LOS; that is, an observer's view path extends linearly from the origin and terminates upon encountering certain materials. In spatial configurations where reflective surfaces are present, observers can gain additional visual information via light reflected off of those surfaces. Features that would normally fall outside of a singular isovist become visible to an observer.

An example of this phenomenon is the use of rear-view mirrors in the operation of vehicles. Drivers rely upon reflective surfaces to extend their gaze to the rear of the vehicle in order to see what is hidden from their front-facing perspective. This visibility can be represented by what we define as secondary and tertiary isovists. These are generated from reflective origins (typically areal or volumetric) that fall within a primary isovist generated from an observer (Figure 10).

The refractive properties of air, water, and other transparent mediums may also serve as generators of secondary and tertiary isovists; however, only in cases where one transparent medium transitions abruptly from one to the other. The bending of light through one continuous medium as a result of refraction or turbulence is beyond this research's scope.

The ability to compute reflection and simulate refraction has been possible for some time in the computer graphics and rendering communities. Those in the architectural realm have perhaps done the most to make these capabilities analytical in solar and urban

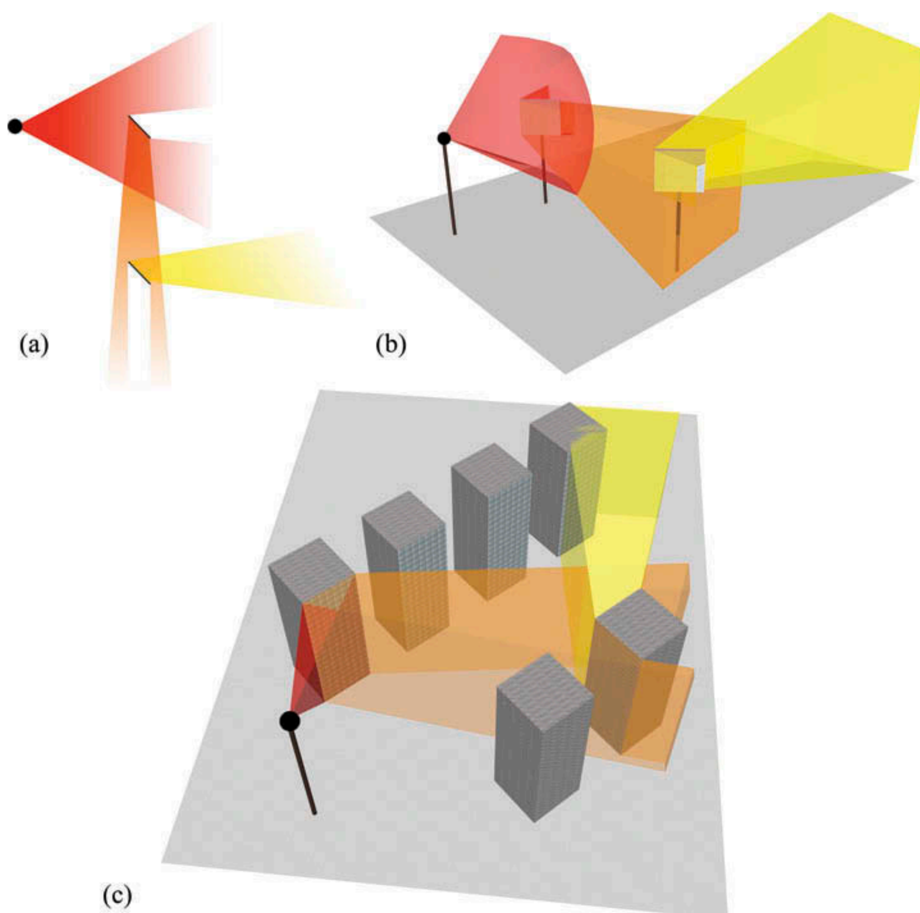


Figure 10. Primary, secondary, and tertiary isovists represented in 2D (a) and 3D (b), and along a hypothetical urban street. Secondary and tertiary isovists are generated from reflective origins that fall within another isovist.

development impact analyses (see Shih and Huang 2001). There remains, however, a considerable opportunity to link these methods to geospatial visibility analysis techniques, and to the problems they are used for – such as privacy and surveillance analysis. In particular, secondary and tertiary isovists (Figure 10) might be used to analyze visual surveillance situations where direct LOS do not exist, but secondary or tertiary LOS do (Figure 10(c)).

The implications of 3D isovists for urban privacy

We introduce the targeted isovist terminology in section 'Targeted isovists and origin-to-target isovist relationships' in order to both clarify existing isovist research, and suggest new approaches to 3D visibility analysis. The targeted isovist emphasizes information relevant to the targeted space. This might allow for a wider variety of visibility analyses not possible through panoptic or constrained isovist geometries. New isovist origin geometries might open further developments.

Prior research has engaged with similar concepts; however, our typologies help to strongly link isovist theory and other forms of visualscapes. Bartie et al. (2008, 2010) developed several methodologies for calculating visibility in urban spatial configurations. Included among these is a LOS-based method for calculating the visible portions of a feature of interest (FOI). The authors differentiate their work from traditional 3D isovist analysis "which quantif[y] the space around the observer", as opposed to their work, where "attention is on how much of a target feature is visible" (Bartie et al. 2010, 519). Our typology unites these conceptual geometries by considering targeted isovists to be subsets of panoptic or constrained isovists. Any LOS analysis that only considers geometries relevant to a FOI would be contained within the larger geometry of a panoptic or constrained isovist.

Conclusions and future work

In this article, we have reviewed the use of isovists and visualscapes for visibility applications. We explored the potential to enhance the analytical capability of isovists, by expanding the geometric conceptualization of isovists, isovist origins, and visibility targets in three dimensions.

We investigated the geometric permutations of isovists that result from different combinations of isovist origins and targets. We introduced an expanded typology of isovists to formalize this work, and as a framework to accommodate geometric complexity in three-dimensional urban environments. These principles were demonstrated with recent research exploring ways to visualize privacy and surveillance regimes in urban environments. We hope this work informs ongoing visibility research, as geographical analyses become more three dimensional.

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