INT. J. GEOGRAPHICAL INFORMATION SCIENCE, 2003
VOL. 17, NO. 1, 25–48

Research Article

Extending GIS-based visual analysis: the concept of *visualscapes*

M. LLOBERA
Institute of Archaeology, University College London, Donald Baden-Powell Quaternary Research Centre, Department of Anthropology, University of Oxford, Oxford, England, UK

(*Accepted 31 May 2002*)

Abstract. A Geographical Information System (GIS) is used to retrieve and explore the spatial properties of the visual structure inherent in space. The first section of the article aims to gather, compare and contrast existing approaches used to study visual space and found in disciplines such as landscape architecture, urbanism, geography and landscape archaeology. The concept of a *visualscape* is introduced in the following section as a tentative unifying concept to describe all possible ways in which the structure of visual space may be defined, broken down and represented within GIS independently of the context in which it is applied. Previous visibility studies in GIS are reviewed and further explored under this new concept. The last section presents the derivation of new visual parameters and introduces a new data structure (i.e. a vector field) to describe the *visual exposure* of a terrain.

1. Introduction

This paper describes the use of Geographical Information Systems (GIS) to study human visual space. To date, the use of GIS to explore human space, i.e. as encountered by an individual, has been very limited. This is partly due to the fact that most GIS operations are based on a traditional geographical view of space which is essentially two-dimensional with a fixed and external frame of reference. The absence of GIS procedures that consider terrain and built environment representations together is a clear indication, among others, of these limitations. Hence, traditional GIS operations are inadequate for developing models of human–space interaction, particularly human perception, whenever a mobile frame of reference is considered. Though some attempts exist to relate GIS with cognition and perception, these have mostly concentrated on landscape preference (Baldwin *et al.* 1996, Germino *et al.* 2001). Ultimately, the design of new GIS routines, and/or the development of new spatial tools that will accommodate human and other factors, will become necessary if cognitive and perceptual factors are to be linked with spatial information. In the meantime, existing GIS can be used to illustrate the necessity and potential of these types of analyses.

The idea that any spatial configuration structures human visual space by virtue of its distribution and geometry, and that such structure can be described spatially

International Journal of Geographical Information Science
ISSN 1365-8816 print/ISSN 1362-3087 online © 2003 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/13658810210157732

using different parameters, underlies the entire paper. Studies that have sought to explore these properties have been developed for the most part within the areas of urbanism and architecture, largely because they have been based on the application of a 'watered down' version of the notion of isovist which permits descriptive parameters to be calculated easily. While visibility studies in 'natural' environments, mostly based on the application of GIS, have not emphasized the structural aspect of visual space, many of the concepts found in these studies, e.g. cumulative viewshed, can still be interpreted as providing a simple description of such structure. The concept of *visualscapes* is introduced here to describe all possible ways in which the structure of visual space may be defined, broken down and represented within GISc independent of the context where it is being applied. Previous visibility studies in GIS are reviewed under the notion of visualscape, and further explored under this new concept. The last section presents the derivation of new visual parameters and introduces a new data structure (i.e. a vector field) to describe the *visual exposure* of a terrain.

The nature of all of the examples used in this paper is purposely generic. Although this limits the possibilities of exploring 'real' implications, it also guarantees the applicability of new concepts to any context.

2. Background

Formal approaches to the study of visual space can be found in various fields, such as urbanism (Batty 2001, Turner *et al.* 2001), architecture (Benedikt 1976), geography (Fisher 1995) or archaeology (Wheatley 1995, Fisher *et al.* 1997, Lake *et al.* 1998). These studies tend to fall into two categories: the built environment and 'natural' landscape.

In the following sections, some of these studies will be reviewed and compared with others focussing on 'natural' landscapes. The following discussions are centered around the basic units of analysis used in both approaches, i.e. isovists and viewsheds.

2.1. *Urban landscape: the study of isovists*

Recently, several works have appeared that focus on the properties of urban or architectural visual patterns, which ultimately seek to elicit and derive possible social implications (Turner *et al.* 2001). Most approaches are based on Benedikt's inspiring work on isovist and isovist fields (1979). In this work, Benedikt defined and explored the concept of an isovist in detail, a notion first introduced by Tandy (1967). This constitutes the basic element of analysis used in recent research on visibility within an urban context. An isovist is defined as a subset of points in space—all of those points in a visible surface D that are visible from a 'vantage' [view] point (x) (Benedikt 1979). However, it is most often thought of in relation to its geometry, i.e. usually as a two-dimensional polygon representing the area of visibility associated with a specific viewpoint. It is vital to note that while isovists have been calculated as two-dimensional entities ever since their inception, Benedikt defined them originally as being three- and four-dimensional (3D + time). Benedikt derived and explored several numerical properties of isovists, such as *area*, *perimeter*, *occlusivity*, *variance*, *skewness* and *circularity* of isovists, and 'mapped' them in order to generate some sort of mathematical scalar field, or isovist field.

Isovists (figure 1) are usually the result of *ad hoc* programming (the exception being CASA's *DepthMap*). Generally, they are derived from urban and architectural plans by disregarding any information on the height variability of urban elements

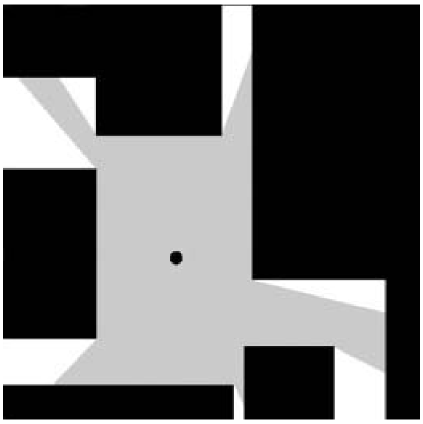

Figure 1. Typical example of an isovist.

(e.g. buildings, fences). The possibility of being able to look beyond an obstacle, once a line-of-sight (LoS) has reached it, is usually never considered. As a result, isovists do not present 'holes', which means that they can be represented easily by *simple* polygons (de Berg *et al.* 1997). An individual positioned at any location in the isovist can walk straight up to the original viewpoint without ever losing sight of it. The calculation of isovists has traditionally been carried out in continuous space, without any need for sampling (isovists are still conceived as continuous). Recently, the possibility of mapping numerical characteristics of isovists back into space has precipitated the adoption of discrete representations (Batty 2001). Discussions on the effects of distance over visibility are not present in these studies because the range of isovists tends to be short within an urban context (Batty 2001). Because of the above factors the computation and description of isovists is a relatively quick and unproblematic process. It can be argued, however, that the restrictions imposed on their calculation may ultimately reduce their usefulness.

Batty (2001) and Turner *et al.* (2001) have recently extended Benedikt's work by representing isovists as a subgraph of a visibility graph (De Floriani *et al.* 1994) from which several properties, such as *average distance*, *minimum distance*, *maximum distance*, *area*, *perimeter compactness* and *cluster ratio*, could be calculated and mapped back into space. When such properties are computed for each point within a sample space, a scalar field is created similar to that found in Benedikt (1979). Both articles discuss the possibility of deriving social information whenever an isovist is treated as a graph.

The process of creating a scalar field, by mapping numerical properties derived from an 'isovist graph' back into space, and the subsequent interpretation of these patterns, is quite critical. Properties of an 'isovist graph' not only describe the interrelationship between a viewpoint and its visible points, but also the interrelationship between each visible point within the isovist (O'Sullivan and Turner 2001). This means that, occasionally, the value at a particular location, or viewpoint, may be due predominantly to the interrelationships among each of the other points in the isovist, rather than to the relationship between the viewpoint itself and its visible points within the isovist. Hence the coupling of a value (describing a certain property) to a location may be very loose and difficult to interpret at times.

An example of the difficulties of interpreting the spatial aspect of visual space is found in Turner *et al.* (2001). In this study, the authors make the claim that the clustering coefficient 'indicates how much of an observer's visual field will be retained or lost as they move away from that point' (Turner *et al.* 2001). Here it is assumed that visual field refers to the visible area associated to a specific viewpoint. If so, this cannot be read, at least not directly, from the definition of the clustering coefficient of an 'isovist graph.' The clustering coefficient of an isovist graph describes the interrelationship between all locations within the visibility graph but does not, at least directly, describe the relationship between a specific location and its neighbors. The next example (figure 2) clearly demonstrates this point. It shows the plan of a room onto which a regular grid has been laid out as a way of sampling the space. In this case, the room could be 3 × 4 m and the sampling rate 1m. The clustering coefficient is defined as:

> the number of edges between all the vertices in the neighbourhood of the generating vertex (i.e, the number of lines of sight between all the locations comprising the isovist) divided by the total number of possible connections with that neighbourhood size [neighborhood being all the vertices that are visible from a location] (Turner *et al.* 2001)

Formally the clustering coefficient is defined as

$$C_i = \frac{|\bigcup \{e_{jk} : v_j, v_k \in N_i\}|}{k_i(k_i - 1)}$$

where the numerator describes the number of line-of-sight (LoS) in an isovist/viewpoint (i) and the denominator represents the number of possible LoS for that same isovist/viewpoint (i).

The clustering coefficient is the same at locations i and j (i.e. $C_i = C_j$), the neighbourhood around both locations is 13, and almost identical in composition (the only difference being that j is part of N_i while i is part of N_j). The number of LoS within this neighbourhood is less than the maximum number of possible LoS for a neighbourhood of similar size, given that 13 out of 7 locations do not have visual contact with g and vice versa. Hence while both locations have the same cluster coefficient it does not follow that the effect of moving from each location to its immediate neighbors is necessary the same. Moving from i to g represents a big visual change, as opposed to moving from j to any of its immediate neighbours. Strictly speaking, how much of an observer's visual field is retained does not follow from the definition of clustering coefficient of an isovist graph.

Looking at the clustering coefficients of points across an area gives an indication

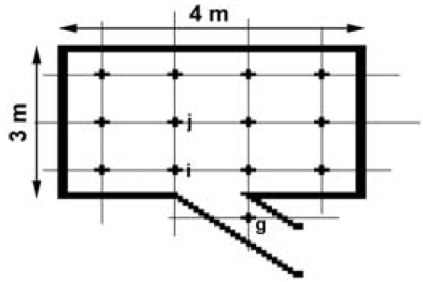

Figure 2. This example illustrates how locations i, j may share the same cluster coefficients but not necessarily the same visual change when moving from them to any of their neighbouring locations.

of the nature of the change in the visual environment but cannot be easily applied to a specific case. While it may be true that locations with high clustering coefficients tend to indicate that there will be small visual variations when moving to neighbouring locations, as it is in the case of location *j*, this implication does not follow directly from having a high clustering coefficient. The identification of a location, such as *i*, in space is significant, as it marks a location (within our sample space) in where some aspect of the visual field changes dramatically (e.g. the shape or area). Although, strictly speaking, the interpretation of Turner *et al.* (2001) does not follow from the definition of the clustering coefficient, the possibility of increasing the number of locations in the sample space does support their original observation.

Outside the context of urban and architectural studies, references on visual analyses tend to use the term viewshed for isovist. Currently, viewsheds are closely linked to the use of commercial GIS and although they are very well established, they have not been explored in the same manner as isovists.

2.2. *Visual patterns in a 'natural' landscape: the viewshed*

The viewshed procedure (used to generate viewsheds) is a standard procedure among most GIS packages today. It is used, essentially, to calculate which locations (i.e. grid cells) in a digital elevation model (DEM) can be connected by means of an uninterrupted straight line (i.e. LoS) to a viewpoint location within any specified distance. Effectively, it calculates which locations or objects are not obstructed by topography and therefore may be visible from the specified viewpoint location. While it is true that for any location to be visible it must be connected by at least one uninterrupted LoS to the viewpoint location, this does not guarantee that it is visible from that viewpoint, i.e. atmospheric conditions may render an unobstructed object invisible. Whether a location, or an object on it, can be distinguished or identified is never considered.

Any interpretation based on the results of the viewshed calculation, particularly when a human component is present, is subject to the limitations of the DEM (e.g. altitude errors, curvature of the Earth); the absence of detailed coverage (e.g. vegetation, built environment); the effect of atmospheric conditions and the ability of the observer to resolve features. Unfortunately a large proportion of examples on the application of viewsheds do not address these restrictions directly (Gaffney and Stančič 1991, Fels 1992, Miller *et al.* 1994, Gaffney *et al.* 1996, Lee and Stucky 1998). While the inclusion of the term view in the term viewshed can be seen as partly contributing to misleading interpretations (Tomlin 1990 for a more neutral term), it is the lack of better algorithms which is ultimately responsible for setting the limits for further interpretations. Gillings and Wheatley (2000) have provided a useful non-technical synthesis on the problems and risks surrounding the use and interpretations of viewshed results.

Viewsheds are most often calculated and represented using a raster data model (though algorithms using triangular-irregular-networks or TINs also exist, see De Floriani *et al.* 1994, De Floriani and Magillo 1999). They are derived by means of algorithms which require terrain heights to be checked along each LoS calculated (Fisher 1991, 1992, 1993). Their computation is therefore far more intensive than the one needed to compute isovists as these are currently found. The nature of the results is also different. Viewsheds are usually irregular and fragmented; often comprising of discrete patches, rather than a single continuous bounded area or polygon. While discussion on the appropriateness and variability of methods for calculating viewsheds has been an important issue (Fisher 1993), it has not been so with isovists. All of these reasons have contributed to viewsheds resisting the type of parameterization that can be found with isovists. Parameters that describe, for instance, geometrical properties such as compactness (Batty 2001) or shape. Instead it is possible, in contrast with isovists, to find several studies in which certain parameters refer to the content in the viewsheds (that is characteristics of the terrain found within the area delimited by the viewshed, Miller *et al.* 1994, Bishop *et al.* 2000, Germino *et al.* 2001). These parameters, however, are seldom mapped back into space in order to generate new surfaces.

In an attempt to overcome these limitations, Llobera (1999) distinguished the *nearviewshed* as the smallest continuous area immediately surrounding a viewpoint and tried to describe some of its characteristics, such as *maximum* and *minimum axis* (maximum or minimum distance), *orientation of maximum* and *minimum axis*, *angle between maximum* and *minimum axis*, as the subset of a viewshed equivalent to an isovist. Given the raster nature of the representation, these parameters proved to be exceedingly coarse and revealed the limitations of using two-dimensional data to explore what is essentially a three-dimensional construct.

3. Visualscapes

In the following sections, visualscape is introduced as a concept within GISc that is analogous to Benedikt's isovist fields (1970), and that may help to unify, under one term, the scope and ideas found in current analyses on 'human' visual space, independently of their scale or context. While the definition provided here is purposely abstract and generic in character, and not all possible combinations of what may constitute a visualscape are necessarily explored, it is hoped that the definition will be seen as an extension to Benedikt's initial ideas.

At a theoretical level, the concept of visualscape (as with isovist fields) finds its source of inspiration in Gibson's (1986) *ambient optic array* insofar as it relates to the visual structure inherent in an environment, although, strictly speaking, a visualscape could only be equated with Gibson's optic array if a light source was also included.

3.1. *Visualscape defined*

A visualscape is defined here as the **spatial representation** of any **visual property** generated by, or associated with, a **spatial configuration**.

To expand:

Spatial representation refers to the way in which a visual property (see below) at a location is stored and represented. This representation is related to a sample space (a discrete space within which observations are taken or calculated at a certain rate) that has a resolution as fine as necessary for the analytical purpose. It is at one, or various, locations in this sample space that an imaginary model of a human individual is situated in order to capture a visual property. Such a model can admittedly be very simple, e.g. the height and orientation of the body, but it is hoped that knowledge in ergonomics and/or human physiology will be incorporated to improve future models. Traditionally, this representation has taken the form of a scalar field (Bendedikt 1970, Batty 2001). Scalar fields are easily created and show the spatial pattern of properties in a familiar way (rasters being GIS analogous to them). This form of spatial representation, however, is not exclusive or the best one for certain purposes. Llobera (in press) demonstrates how the visual structure of simulated landscape, and that associated with a series of antennae, can be represented using a vector field, and that such a representation is far better suited to describe visual changes related to changes in body orientation during movement along a path, than a scalar field.

Visual property refers to the measure of any 'visual characteristic' associated with a location in the sample space. This property may be the description of some aspect linked to the viewshed/isovist generated at that or some other location. An example of the former, for instance, would be the mapping of the average distance of the isovist at each location in a sample space (Batty 2001), an example of the latter may be a cumulative viewshed, where locations store the number of times that they are visible from other locations.

Finally, the notion behind what constitutes a **spatial configuration** lies at the heart of the visualscape concept. The idea here is that by varying the selection of what spatial components make up a spatial configuration, we can vary the scope, scale and intent of the visual analysis. The analytical potential of the visualscape is not only linked to the choice of what constitutes the spatial configuration but also to the way in which it is represented and stored, whether by means of traditional spatial primitives, e.g. a single point to represent a building, or more complex data structures, like 3D solid models. So far the former way of representing spatial structure has prevailed in GIS, but the possibilities of using more complex spatial data structures are near and likely to precipitate the generation of new data. For instance, to understand the visual impact that a building with some symbolic relevance, such as a temple (e.g. *il duomo de Firenze*), has on its surroundings, and to answer questions such as: where can it be seen from? How much of it can be seen at each location? How does its visual presence change as we walk to and from, or around it? As important is the fact that the visual structure of specific spatial components can be targeted, since this allows us to incorporate and explore another of Gibson's important contributions, the idea of perception as the education of attention. As a landscape evolves through time, so does the relevance of features in it (whether natural or built). During some periods certain features become more salient than others ('anchorpoint theory' by Golledge 1978). Understanding what is the nature of the visual structuring during a certain period, and how it transforms through time, can be achieved by generating and studying the various visualscapes associated with these salient features (Thomas 1993, Tilley 1994). The relevance of varying the spatial composition to study visual structure is illustrated in the following figure (figure 3). In this case the visual areas associated with an entire house, the façade and the interior are broken down one by one to create a set of nested spaces. The ability to recognize such spaces may be used to understand how distinct spatial patterns of social behaviour surrounding a house are generated.

To summarize, the notion of a visualscape is put forward here in the hope that it will be a useful GISc term used to describe the fact that any spatial configuration creates its own visual structure which:

- Can be studied in its entirety or with respect to any relevant subset of the spatial configuration.
- Can be spatially represented in various ways (e.g. scalar or vector fields).
- Is essentially three-dimensional. They may be explored using any of the standard concepts that apply to 3D surfaces (figure 4).

Figure 3. Breaking down visual structure of a single monument into a set of nested visualscapes.

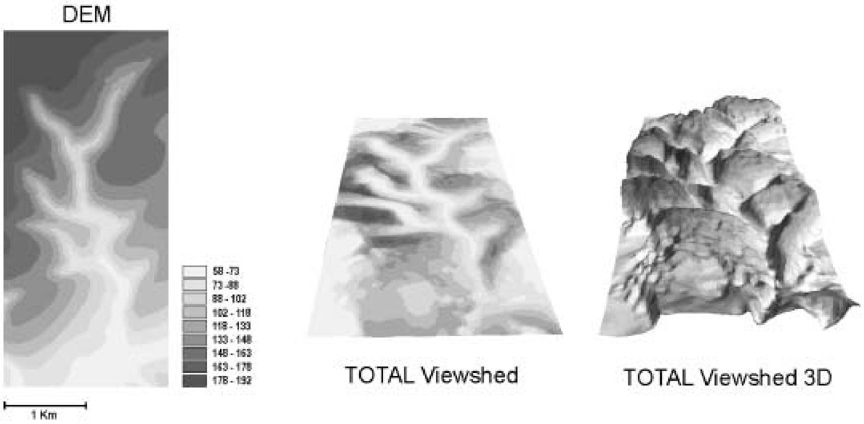

Figure 4. Within GISc visual patterns have generally been approached as two-dimensional patterns, however, the possibility of new analytical possibilities becomes clearer when visual information is better understood as a 3D surface.

- Can be described by means of multitude of parameters, as shown in some urban studies, and eventually mapped back into space for further research. Besides a few exceptions (Bishop *et al.* 2000, Germino *et al.* 2001), this possibility has seldom been explored in the context of current GIS visibility applications. There are even fewer examples (most notably O'Sullivan and Turner (2001)) of visual parameters being mapped back into space and their spatial properties further studied.
- Occurs both in 'natural' and urban landscapes. The adoption of new spatial structures and the development of analytical procedures to explore the benefits

of such representations will, in this author's opinion, unite efforts to study visual space.

3.2. *Cumulative and total viewsheds*

Perhaps the most popular concept used to explore visual space in a 'natural' landscape has been the *cumulative viewshed* (Wheatley 1995), sometimes called *times seen* (Fisher *et al.* 1997). Cumulative viewsheds in general are created by calculating repeatedly the viewshed from various viewpoint locations, and then adding them up one at a time using map algebra (Tomlin 1990), in order to produce a single image. The result tells us how many of the viewpoints can be seen from, or are seen at each location, i.e. their *visual magnitude*. Fels (1992) distinguished two types, depending on whether the offset (e.g. representing the height of an individual) was included at the viewpoint (*projective viewshed*) or at the target location of the LoS (*reflective viewshed*). *Total viewsheds* are created in the same way as a cumulative one except that all locations are employed. Lee and Stucky (1998) distinguished two types of total viewshed based on the location of the offset on the viewpoint (*viewgrid*) or the target (*dominance viewgrid*).

Cumulative and total viewsheds are subject to the same limitations as single viewsheds (Gillings and Wheatley 2000). In both, locations near to the boundaries of the study area suffer from an edge effect, i.e. fewer locations are available, which in the case of a total viewshed can be calculated as a function of the position of each viewpoint location and the radius used for the viewshed, and represented as an additional raster or scalar field. Given the limitations of the viewshed (i.e. no distance attenuation), this edge effect decreases once the radius in the viewshed exceeds the radius of the largest possible circle that can be fully contained within the study area. From that radius onwards, the number of locations within the study area surrounding any location tends to converge towards the maximum number of locations as the value of radius reaches the maximum (Euclidean) distance separating any two locations. At that point, and given the lack of visual attenuation with distance, any location is theoretically visible for any other, no matter where it might be located.

Both cumulative and total viewsheds are examples of visualscapes that can be calculated using standard GIS. They use a set of points to describe the spatial configuration (differing only in the number), as a visual property, they record the number of locations that may be visible, to or from, each point in the spatial configuration and present this information as a scalar field.

In landscape planning, cumulative viewsheds have been used to determine visual impacts (Fels 1992). In archaeological landscape research, they have been used primarily to discuss the intervisibility level among monuments, in order to determine social cohesion and the importance of visible awareness, as a way of establishing territorial rights (Wheatley 1995), or to assess the level of cross-visibility (Llobera 1999) or visual continuity among monuments belonging to different periods (Gaffney *et al.* 1996).

The sole use of cumulative viewsheds as a possible measure for inter- and cross-visibility capitalizes on a static and 'pointillist' view of space. A view where the focus of the analysis is on understanding the relationship between points in isolation, and where concern about space in-between is lost and deemed meaningless and inert. The cumulative viewsheds calculated for a set of features provides a simple description of the visual structuring that these generate. At a very basic level, it can be used to identify where the visual presence of these features may be greatest, providing a series of ‘anchorpoints’ (Golledge 1978) integral for building a sense of place. In order to establish the significance of the visual patterns found in a cumulative viewshed, whether they conform to our expectations given the existing terrain, or to some other spatial configuration, it is necessary to establish some sort of comparison. Such a comparison may be obtained by calculating the cumulative viewshed of locations obtained through some sampling strategy and comparing them with the original cumulative viewshed (Lake *et al.* 1998) or by calculating the total viewshed for the entire terrain (figure 5). Both strategies provide the information necessary for implementing, if required, statistical measures of comparison (not shown here). While the sampling strategy is computationally less intensive, the scope of the results is generally bounded to the questions at hand (e.g. are these patterns significant?) and cannot be incorporated as easily as total viewsheds in future research (see below).

While cumulative viewsheds may be used to describe the visual structure generated with respect to certain locations, or features on them, the total viewshed provides a first description of the visual structure for an entire terrain. Figure 6 shows the total viewshed for different types of landscapes. These have been calculated using the same offset of 1.74 m at both the viewpoint and target location.

Simple histograms, and/or more sophisticated methods (e.g. kernel density estimates, image analysis methods) can be employed to examine the values obtained in the total viewshed of a terrain, in order to identify locations with similar visual magnitudes. Figure 6 shows, for instance, the total viewshed for three different terrains, and their respective histograms (all have been standardized to the same bin-width and terminal points). In addition, each total view has been reclassified into three different categories to facilitate easy comparison. The following discussion results from the visual examination of the histograms and re-classified images.

By comparing the histograms alone it is clear that unlike other terrains, the ridge landscape does not contain locations from which the entire terrain is visible, in fact the maximum number of visible locations corresponds to half of the total area. This is because the ridge is wide, thus impeding views of both sides simultaneously. The ridge is effectively acting as a visual barrier. This landscape is visually well defined and very homogeneous, given the large number of locations sharing the same level of visual magnitude. Its histogram seems to point out the existence of two distinct clusters centered at a low visibility level (bin 400–600), and the other at a medium low level (≈ 2500). However, the sharp peaks also indicate the possibility of acute visual changes (further analyses may be achieved by calculating the spatial variogram of the total viewshed). The upland/lowland landscape is the only one of the three

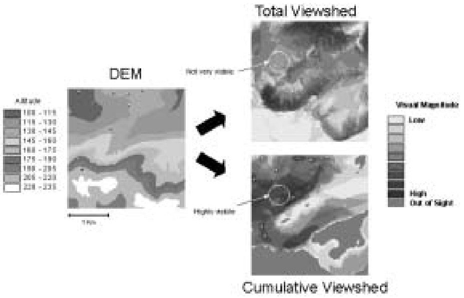

Figure 5. Comparison of a cumulative viewshed and a totalview. Darker areas represent higher visual magnitude.

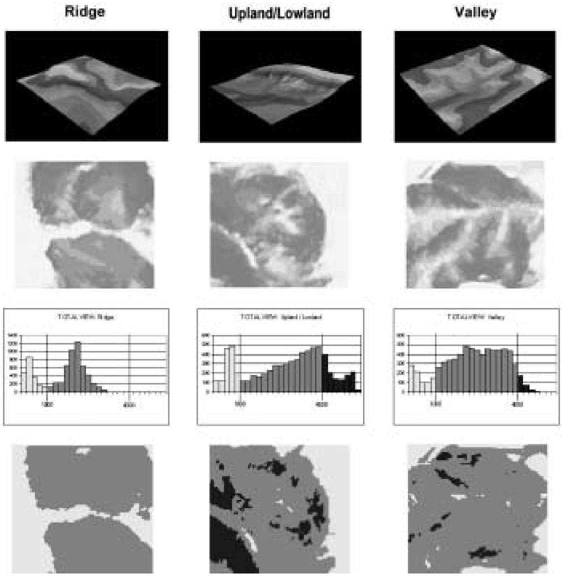

Figure 6. The total viewshed and histogram for three different types of landscapes. All histograms have the same bin-width and terminal points (darker areas represent higher visual magnitude). Last row shows all three total viewsheds reclassified using the same criteria points.

examples that contains locations from where the entire terrain is visible. The histogram of this landscape shows the possibility of well differentiated visual clusters. The same applies to the ridge landscape, the histogram shows that the transition from some clusters to others can at times be quite sharp indicating the existence of abrupt visual changes. The largest classification (dark grey) shows a trend in which the number of locations with greater visual magnitude increases steadily, spatially this seems to correlate with an increase in visibility from right to left (the right being dominated by locations with low visibility). Finally, the valley landscape shows an even spread of locations with different visual magnitudes, i.e. less abrupt changes. As might be expected given the terrain geometry, the valley landscape is visually diverse but compact at the same time, i.e. there are many locations with different but related visual magnitudes.

Given that, in this case, the same offset was used at both the viewpoint and target location during the viewshed calculations, it is possible to read the histograms in relation to intervisibility. Landscapes with high intervisibility levels are characterized by a greater accumulation of locations at the higher end of the histogram. The ridge landscape is characterized by two very well defined groups of locations with low and medium-low intervisibility levels, while the intervisibility for the highland/lowland landscape is much more evenly spread although two groups of locations, with low and relatively high intervisibility, can also be distinguished. Of all the landscapes, the valley type offers the most even spread of intervisibility, mostly concentrated within the medium-low to the medium-high (for similar discussions see also O'Sullivan and Turner 2001).

The creation of totalviews can be manipulated so that the viewshed at each viewpoint is calculated only for those locations within a certain distance band.

Rather than calculating what is visible from the viewpoint location to the maximum radius, say r_{max}, the visibility can be calculated, for instance, for any distance r_1 away from the viewpoint, where $0 < r_1 < r_{max}$, to another arbitrary distance r_2, where $0 < r_1 < r_2 < r_{max}$. This allows us to study the visual impact that each location has at various ranges (figure 7). That is, it shows how important each location is when it is part of the foreground, middleground or background. In this case, as opposed to the previous example, these 'partial' total viewsheds are normalized by the maximum number of locations that are potentially visible within each distance band. This is done to compensate for the fact that in some occasions the number of locations, contained within a particular distance band, can be severely reduced at certain positions in the study area.

The intersection of linear features, such as walking paths, with total viewsheds provides an approximate indication of the nature of visual changes along a path (Fisher 1995, Batty 2001). This approach can be extended to other visualscapes, e.g. generated by a different spatial configuration such as a cumulative viewshed or by mapping out different visual properties (Batty 2001). In addition, Lee and Stucky (1998) have already shown how total viewsheds may be reclassified and used in combination with cost surface analyses to generate paths of different visual qualities. The following example discusses some simple possibilities.

Figure 8(*a*) shows a valley-like landscape which, at first glance, seems relatively smooth. The total viewshed for the same landscape, shown right beside it (figure 8(*b*)), has been given further relief using standard hillshade functionality, as found in most GIS. In spite of its simplicity, the image provides immediately a good indication of the amount of visual complexity inherent in it and an appreciation of the visual changes that someone moving in the landscape may encounter. These changes become more apparent when examined along a track or path (figures 8(*c*), (*d*)). In figure 8(*e*), the cross section of the total viewshed along path A shows how the visual magnitude increases quite steadily until it reaches a maximum towards the end of the route, after which it decreases very rapidly. The scenario is totally different for path B (figure 8(*f*)) where changes in the visual magnitude occur in a roller-coaster fashion. Initially, the path is characterized by a steady descent into what appears to be a large visual enclosure, as seen in figures 8(*b*), (*d*). This is followed by a plateau

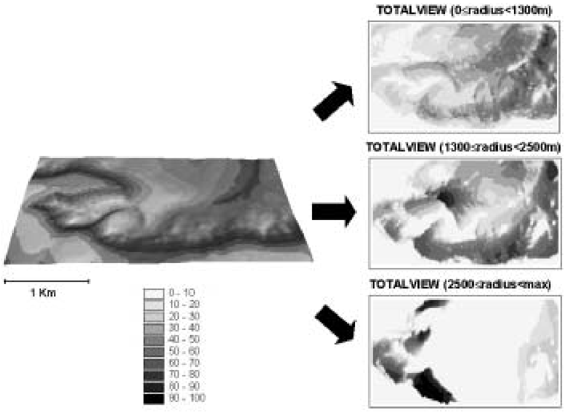

Figure 7. Foreground, middleground, background defined, for simplicity, using arbitrary Euclidean distances. Darker areas represent higher visual magnitudes.

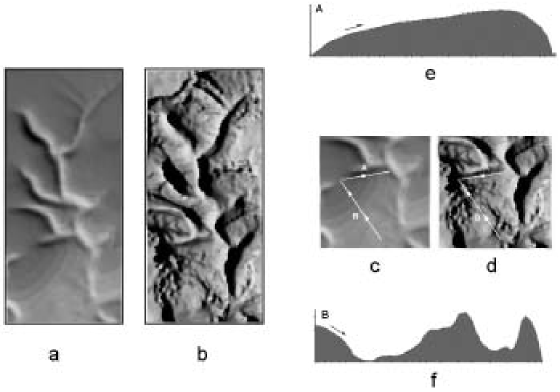

Figure 8. Profile of linear features (e.g. a path) on a total viewshed.

and a pronounced increase in visual magnitude. The path then drops sharply into a second possible enclosure, not as deep as the first one, with pronounced boundaries. After an extremely steep ascent the visual magnitude plunges down dramatically towards the end of the path.

3.3. *Visual prominence*

An (intuitive) understanding of something being **prominent in space** arises after some sort of comparison has been established between the level, or amount, of some property (p) at a location (l), with those found at adjacent locations. Thus it can be said that some idea of neighbourhood, i.e. what constitutes neighbourhood, is implied in the comparison. Many criteria may be used to define what is a neighbourhood or what locations are part of it, here a neighbourhood will be defined by reference to an arbitrary Euclidean distance around any location. The area, comprising all locations within this radius, will define the neighbourhood at any location. Once a neighbourhood is defined, it is possible to produce a simple definition of prominence,

> Prominence of a property p, at any location i, $\mathrm{Prom}(t)_p$ is defined as the average difference between the property at that location $p(i)$, and that found at each of the other locations j_n, $p(j_n)$, within an arbitrary neighbourhood of i, N_i, such that given an arbitrary distance where N_i is the neighbourhood of i, $N = \mathrm{Card}(N_i)$ and $n \in N$ (Natural numbers).

$$i\ Prom(i)_p = \frac{\sum_{j_n \in N_i} p(i) - p(j_n)}{N} \qquad (2)$$

The values for the prominence at any location can have any positive or negative value. The upper and lower bounds will change with each neighbourhood size. The value and sign of the prominence reflects the morphological character of the location. For example, when calculated using a DEM, i.e. altitude being the property that is being compared, higher positive values tend to indicate a sharper hill-top, while more moderate values point towards a more rounded hill-top; values close to zero indicate flat locations and negative values channel- or pit-like locations. It is important to note that the definition at this stage does not include any sort of normalization. This is because the index may be normalized in various ways; the normalization of the entire raster by the maximum prominence value produces a result that is informative, if the analysis is restricted to one image and to its entirety. However, if the analysis represents the comparison of indexes throughout various neighbourhood sizes (figure 10) then it is preferable to normalize each value by the local maximum found within each neighbourhood.

It is fairly obvious from the definition that a prominence index can be derived for different properties or magnitudes. Here, two different, though related, types of prominence are generated, a topographic and a visual prominence. The former is defined by reference to the altitude (derived from DEM) while the latter uses the visual magnitude as described by the total viewshed. Both prominences tend to be easily interchanged, i.e. more prominent locations are thought of as being visually prominent as well, but as figure 9 shows the relationship between topographic and visual prominence is not always straightforward. Such a comparison helps investigate the interplay between physical and visual aspects in a landscape. In this case, we can detect locations that have a high visual magnitude (from where we can see a lot of terrain or from where one can be seen easily, if we accept intervisibility) but are not themselves physically prominent.

Figure 10 shows the visual prominence for different neighbourhood sizes. In this case, initial prominence values were transformed and normalized using local maxima, i.e. the maximum prominence value found within the neighbourhood at each location. Calculating visual prominence for various neighbourhoods allows determining at which scale a location can start to be considered as being visually prominent and/or to identify locations that for instance, maintain a high level of prominence independently of any scale. Such locations are very significant as they tend to be important territorial landmarks and provide useful navigational information about the physical

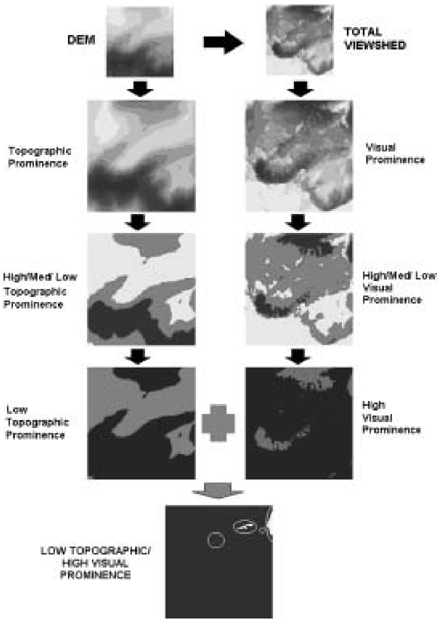

Figure 9. An example comparing topographic prominence with visual prominence. Here both prominences have been calculated for the maximum radius. Both, topographic and visual prominence images are reclassified into high, medium and low values. These are further reclassified and combined in order to obtain locations with low topographic and high visual magnitude.

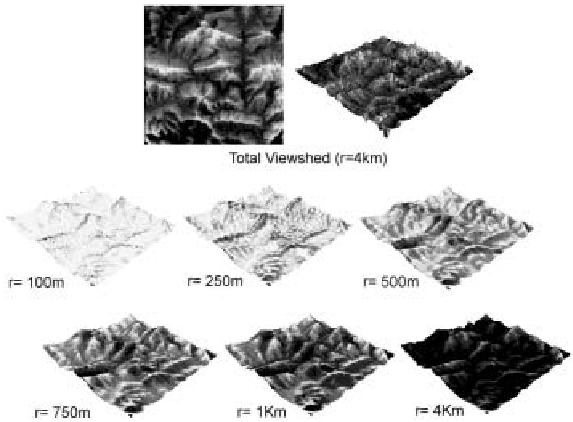

Figure 10. Visual prominence image. The top two images show the totalview for a landscape. These are followed by the visual prominence at various scales, the more visually prominent a location the lighter it appears.

structure of the landscape. Elsewhere Llobera (2001) has shown how prominence at various scales may be combined together and mapped to create a single raster that describes how it changes at each location. It points towards the possibility of describing prominence as a signature (throughout different scales) whose characteristics may be mapped back into space.

To summarize, cumulative and total viewsheds can be used to describe and explore, at a basic level, the visual structure that a spatial configuration, such as the physical topography of a landscape, generates. Properties of this structure can be studied using traditional GIS capabilities (e.g. histograms, reclassification, etc.) and/or by further manipulating them as shown through the visual prominence example. However, the description they offer remains relatively coarse due to factors such as: the sampling interval (i.e. raster resolution), choice of radius, sensitivity of the LoS algorithm and in particular, the choice of visual property that is being recorded, in this case using a Boolean value to describe in-sight or out-of-sight.

3.4. *Visual exposure*

Reference to the more dynamic aspect surrounding visibility was present in the previous discussion on total viewsheds (Batty 2001, Lee and Stucky 1998) but was not really dealt with directly. Such absence among GIS and other spatial studies may be partly the consequence of relying heavily on two-dimensional spatial representations, given their obvious limitations and the fact that such representations may lead researchers to think in a 'static way'.

The limitations of current approaches are important as they hinder our understanding of visual space, especially when movement, and therefore change, has been identified as a key element in visual perception (Gibson 1986). Works as comprehensive as those cited above made only limited reference to this aspect, concentrating instead on the various visual parameters as **static** attributes of space, without further exploring their change in space.

In the following examples the dynamic aspect of visualscapes is considered by concentrating on the study of *visual exposure*, another type of visualscape. Visual exposure is created by assigning to each location in our sample space a measure of the visible portion of whatever is the focus of the investigation, whether the entire landscape or a set of features. Previous work by Travis *et al.* (1975) and Iverson (1985) showed the importance of mapping how visible each location in a landscape (i.e. DEM) (i.e. cell) from a viewpoint was and pointed out the possibility of doing the same with respect to specific landscape features. When calculated in relation to some feature it can be thought of as a description of how much the feature occupies the field of view of an individual at any location. The stress is on the visual patterns created by the physical presence of a feature (i.e. its visible portions). Cumulative and total viewsheds provide a crude depiction of these patterns but their description is not sensitive enough and requires, in the case of a cumulative viewshed, the presence of at least two or more features. The interest here is in determining **how much** of a feature or a terrain is visible at each location, rather than finding out whether a location is visible or not (or how many times it is visible).

On this occasion, *visual angles* are used to generate visual exposure, i.e. visual property. They describe the visible span (both horizontal and vertical) of a feature or terrain facet that can be seen at any viewpoint location, and are well suited to describe the visual exposure of a feature as the field of view of an individual is generally described in terms of angular ranges. Intuitively, the closer we are to the feature the more we expect to notice it, as its presence occupies more of our field of view. Figures 11–15 illustrate the possibilities for a very simple feature (ideally this can be extended to consider full three-dimensional objects).

Figure 11 shows feature *A*, a vertical pole with a height of 10 m, which could represent a communications antenna. The visual exposure for feature *A*, after calculating 'vertical' visual angle with a sampling frequency of 5 m, is shown in figure 12. Because values at locations near the pole are very high in comparison with those further away, it is necessary to use an adequate colour palette, where higher outliers are grouped into one single category.

One of the benefits of mapping out the visual exposure is that we can use real numbers (floating-point), which translate into smoother surfaces than those obtained for cumulative or total viewsheds. This, in turn, allows us the possibility of further processing the visual exposure using standard mathematical techniques. By calculating the local gradient of the visual exposure, i.e. the first surface derivative (slope), we can identify where (local) visual changes occur, their magnitude (darker areas representing higher change) and the direction of change, e.g. direction in which maximum visual exposure is obtained (see figure 13). From this it follows, that the

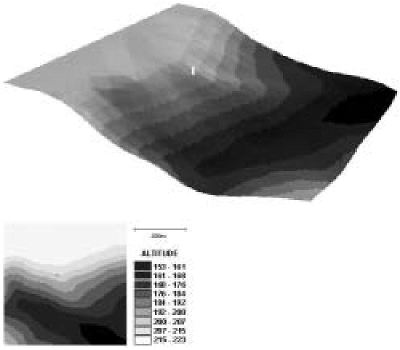

Figure 11. Feature *A* (pole) on example DEM.

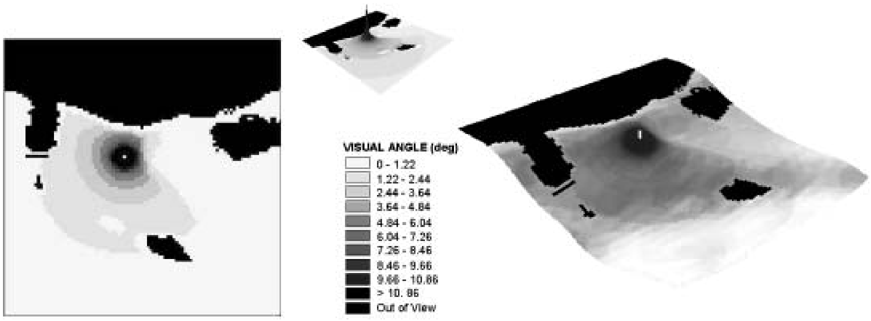

Figure 12. Magnitude of visual angle calculated for feature *A*. In plan view, as a 3D surface (small inset) and on the DEM.

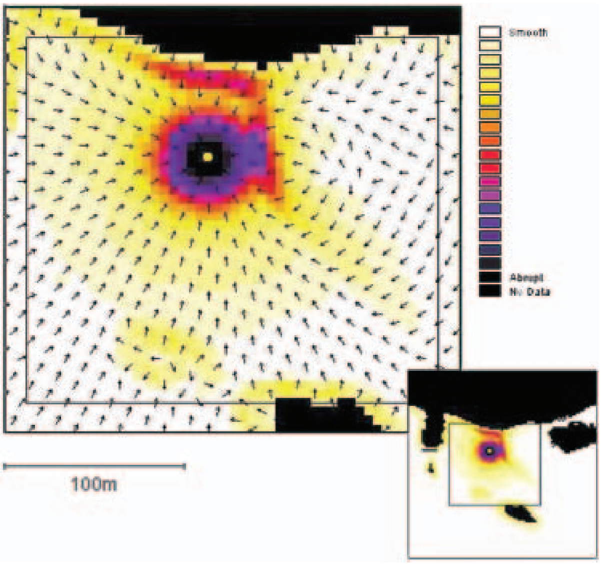

Figure 13. Close-up showing local visual change, sense and direction of maximum gain.

opposite direction represents the quickest way to get out of sight from the feature, and that by moving perpendicular to this direction will not incur any visual change.

Figures 14 to 15 describe the shape of the visual change. These images were obtained by calculating the second (discrete) derivative of the visual exposure in the direction of maximum change, and in the orthogonal direction.

The idea is better understood by imagining the visual exposure as a three-dimensional representation of a landscape where instead of altitude values (as we would have with a DEM) these are magnitudes of solid angles that describe how much we see of feature *A*. Moving up or down this 'landscape' along contours represents changes in visual exposure while movement preserves the same level of visual exposure. If the amount or rate of visibility associated with the feature increases each time more along a certain direction we get a concavity (see figure 15), while if it decreases we get a convexity.

Figures 17 and 18 are based on the same principles as figure 14 except that it shows the shape of the visual exposure, the concavity or convexity, in the orthogonal

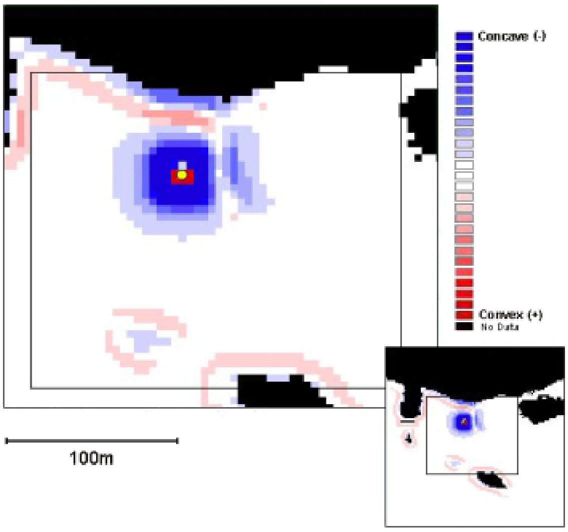

Figure 14. Local curvature of the visual exposure **in the direction of maximum change**. The shading indicates the intensity of the curvature.

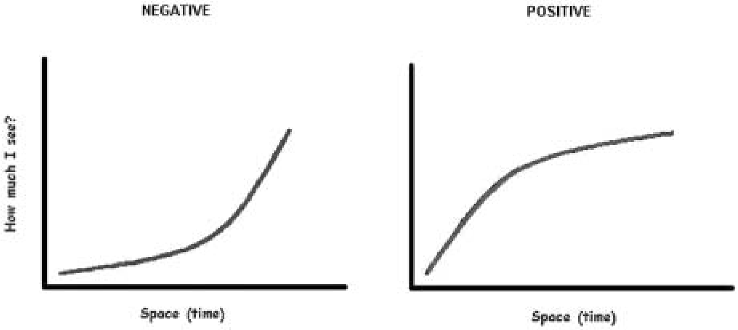

Figure 15. Profile cut in the **direction of maximum change** showing the concavity and convexity of the visual exposure for feature *A* in figure 14.

direction of maximum change (see figures 19 and 20). Potentially it can be used to identify locations where we would get ‘visual corridors’ (i.e. concavities, or more visibility towards the sides than towards the middle) and ‘visual ridges’ (i.e. convexities, or more visibility towards the middle than towards the sides).

So far, mapping where changes in visual exposure occur and the nature of those changes has only been explored in relation to the direction of maximum change (given by the local gradient). While not shown here, these calculations could be easily adapted to allow mapping similar information for any direction of movement by applying the general definition of a *surface directional derivative* (from where the gradient derives). Similarly, methods of morphometric characterization (Wood 1996) as found for DEMs, could be extended to the visual exposure (and other visualscapes) to describe their morphological characteristics, i.e. shape, properties.

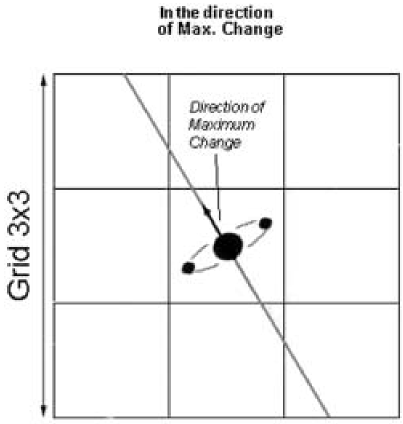

Figure 16. In this occasion the concavity and convexity are measured locally (i.e. within a 3 × 3 window) in the direction of maximum change in figure 14.

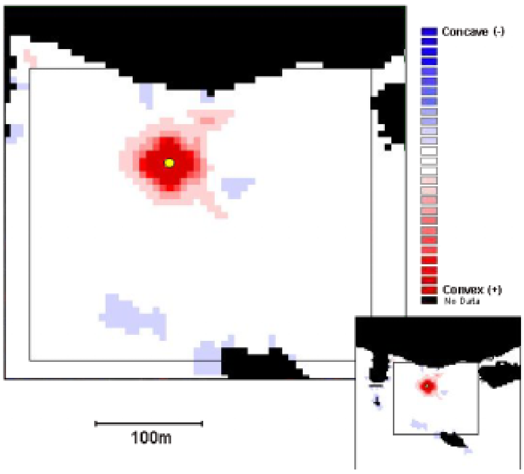

Figure 17. Local curvature of the visual exposure **orthogonal to the direction of maximum change**. The shading indicates the intensity of the curvature.

Several interesting insights can be drawn from the previous examples. The sampling rate that was used (i.e. 5 m intervals) is likely to be inadequate for modelling the visual impact that features have on people, at least, if these are meant to be calculated at a close range. The closer an observer is to the feature or part of the landscape of interest, the smaller the distance the viewer has to move in order to appreciate a substantial change, and vice versa. This observation points towards an important finding, the use of a scalar field or raster to represent visual information limits the possibility of detecting changes to those we would observe at a constant speed of movement.

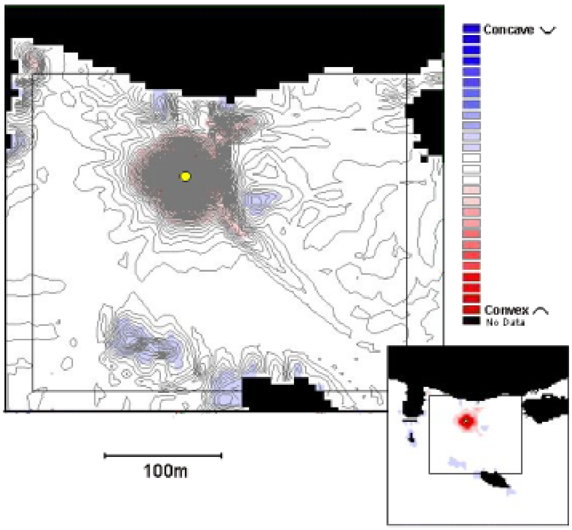

Figure 18. Local curvature of the visual exposure **orthogonal to the direction of maximum change**. The shading indicates the intensity of the curvature. Contour lines are added to give a better horizontal sense.

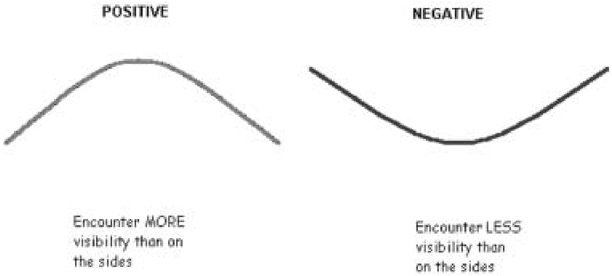

Figure 19. Profile cut in the **PERPENDICULAR direction of maximum change** showing the concavity and convexity of the visual exposure for feature *A*.

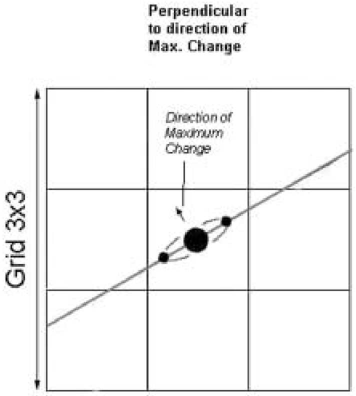

Figure 20. The concavity and convexity are measured locally (i.e. within a 3 × 3 window) perpendicular to the direction of maximum change.

To conclude this section, a final example of the visual exposure as a vector field is provided. Figure 21 shows a landscape represented by a TIN data structure. To calculate a vector version of the visual exposure for an entire landscape, the Digital Terrain Model (DTM) is sampled at a certain fixed rate (20 m), and the following procedure is repeated at every target location (figure 22).

1. A viewpoint location is selected.
2. An orthonormal vector (i.e. perpendicular vector with a magnitude of one) to the terrain is calculated at the target.
3. A normal LoS vector is also calculated with its origin on the target and direction pointing towards the current viewpoint.
4. The visual exposure is the vector obtained by projecting the surface orthonormal onto the LoS. In this case, the vector is multiplied by an additional factor derived from the distance between the viewpoint and the target point (the further away, the less you see).

The sum of all vectors obtained after paring the target location with every viewpoint location represents the total visual exposure for that target location. Figure 23 shows the total viewshed and the magnitudes of the vectors describing the total visual exposure for the same landscape side by side. This is similar to using a vector field, in this case to represent the total visual exposure of a landscape, is an important improvement over other ways of representation for it not only provides a measure of a visual property but also its direction, information that is indispensable in order to model and map more efficiently visual changes due to movement (Llobera in press).

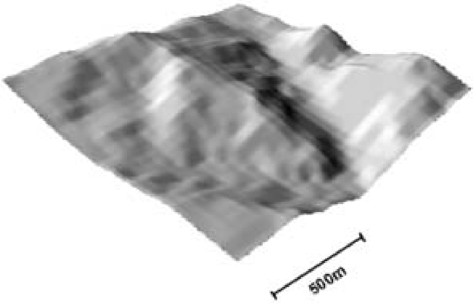

Figure 21. TIN representation of a landscape.

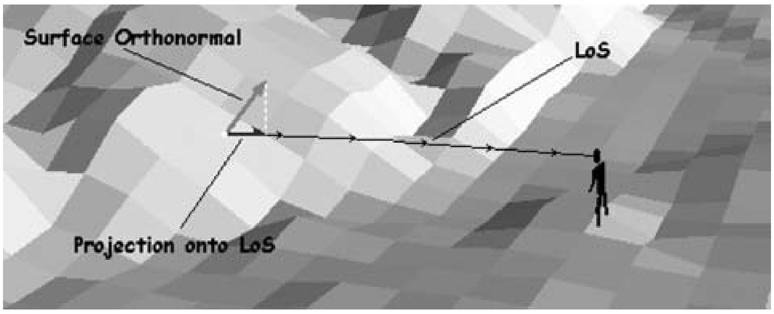

Figure 22. Generating a vector field to describe visual exposure.

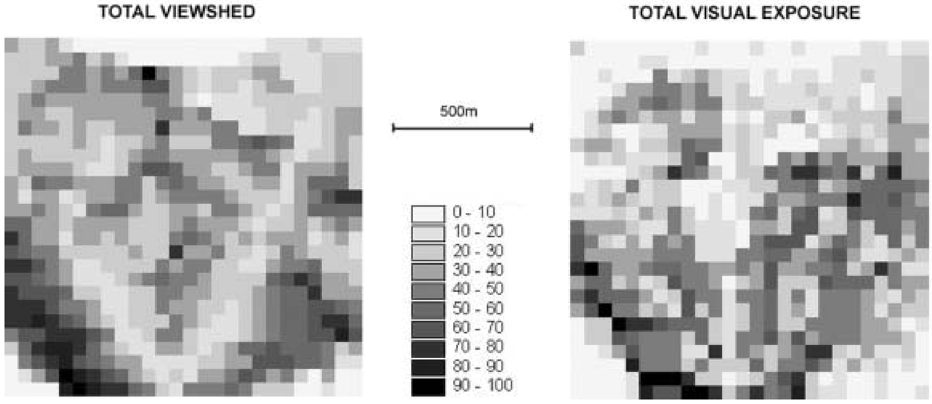

Figure 23. Comparison of the Total viewshed with the Total visual exposure for the previous landscape.

4. Conclusions

The exploration of visual space crosses various disciplines. This paper provided a critical synthesis of some of the issues associated with the analysis of visual space that are relevant to many disciplines, and attempted to unite them under a single common notion: visualscape.

Any spatial configuration, whether it is the physical topography of a 'natural' landscape or the façade of several buildings, structures space visually. This paper showed how isovists, isovist fields, cumulative viewsheds and total viewsheds may be interpreted as providing simple descriptions of such structure, i.e. visualscapes, that represent just as a tiny fraction of the possible ways in which this structure can be described and represented. With such interpretation in mind, the characteristics of total viewsheds were further explored and the idea of visual prominence was put forward. Visual exposure was introduced as a new visualscape that describes how much of a feature, or an entire landscape, can be seen at any location. Properties of the visual impact were illustrated using several examples, and the possibility and benefits of using a vector field to represent the visual exposure were discussed.

While it is true that factors such as landscape or environmental perception cannot be reduced to a mere physical measure of some structuring property of space, no matter how complex, their role nevertheless, is an important one which is only now beginning to be explored.

Underlying the content of this paper is the realization that in order to understand how people experience and associate meaning to space we need to develop new analytical tools that help us retrieve the structure of space as it is encountered and unfolds in relation to a mobile subject. Studies of visual space fall within this orientation.

Acknowledgments

I would like to thank James McGlade and Aaron Shugard (Institute of Archaeology, UCL), Pamela Wace and Helen Walkington (Oxford University), Mike Batty (CASA, UCL) and particularly two anonymous referees for useful comments on earlier drafts of this paper.

References

Baldwin, J., Fisher, P., Wood, J., and Langford, M., 1996, Modelling environmental cognition of the view with GIS. In *Proceedings of the Third International Conference/Workshop on Integrated GIS and Environmental Modeling*.

Batty, M., 2001, Exploring isovist fields: space and shape in architectural and urban morphology. *Environment and Planning B*, **28**, 123–150.

Benedikt, M. L., 1979, To take hold of space: isovists and isovist fields. *Environment and Planning B*, **6**, 47–65.

Bishop, I. D., Wherrett, J. R., and Miller, D., 2000, Using image depth variables as predictors of visual quality. *Environment and Planning B*, **27**, 865–875.

de Berg, M., van Kreveld, M., Overmars, M., and Scharwrzkopf, O., 1997, *Computational Geometry* (Berlin: Springer Verlag).

De Floriani, L., and Magillo, P., 1999, Intervisibility on terrains. In *Geographic Information Systems: Principles, Techniques, Managament and Applications*, edited by P. A. Longley, M. F. Goodchild, D. J. Maguire and D. W. Rhind (London: John Wiley & Sons), pp. 543–556.

De Floriani, L., Manzano, P., and Puppo, E., 1994, Line of sight communication on terrain models. *International Journal of Geographic Information Systems*, **8**, 329–342.

Fels, J. E., 1992, Viewshed simulation and analysis: an interactive approach. *GIS World*, **Special Issue July**, 54–59.

Fisher, P., 1991, First experiments in viewshed uncertainty: the accuracy of the viewshed area. *Photogrammetric Engineering and Remote Sensing*, **57**, 1321–1327.

Fisher, P., 1992, First experiments in viewshed uncertainty: simulating fuzzy viewsheds. *Photogrammetric Engineering and Remote Sensing*, **58**, 345–327.

Fisher, P., 1993, Algorithm and implementation uncertainty in viewshed analysis. *International Journal of Geographic Information Systems*, **7**, 331–347.

Fisher, P., 1995, An exploration of probable viewsheds in landscape planning. *Environment and Planning B*, **22**, 527–546.

Fisher, P., Farrelly, C., Maddocks, A., and Ruggles, C., 1997, Spatial analysis of visible areas from the bronze age cairns of Mull. *Journal of Archaeological Science*, **25**, 581–592.

Gaffney, V., and Stančič, Z., 1991, *GIS Approaches to Regional Analysis: a Case Study of the Island of Hvar* (Ljubljana: Znanstveni institute Filozofske Fakultete, University of Ljubljana).

Gaffney, V., Stančič, Z., and Watson, H., 1996, Moving from catchments to cognition: tentative steps towards a larger archaeological context for GIS. *Anthropology, Space and Geographic Information Systems*, edited by M. Aldendefer and H. Maschner (Oxford: Oxford University Press), pp. 132–154.

Germino, M. J., Reiners, W. A., Blasko, B. J., McLeod, D., and Bastian, C. T., 2001, Estimating visual properties of Rocky Mountain landscapes using GIS. *Landscape and Urban Planning*, **53**, 71–84.

Gibson, J. J., 1986, *The Ecological Approach to Visual Perception* (New Jersey: Lawrence Erlbaum Associates Inc.).

Gillings, M., and Wheatley, D., 2000, Vision, perception and GIS: developing enriched approaches to the study of archaeological visibility. *Beyond the Map*, edited by G. Lock (Amsterdam: IOS Press), pp. 1–28.

Golledge, R., 1978, Learning about urban environments. In *Timing Space and Spacing Time I: Making Sense of Time*, edited by T. Carlstein, D. N. Parkes and N. J. Thrift (London: Edward Arnold).

Iverson, W. D., 1985, And that's about the size of it: visual magnitude as a measure of the physical landscape. *Landscape Journal*, **4**, 14–22.

Lake, M. W., Woodman, P. E., and Mithen, S. J., 1998, Tailoring GIS software for archaeological applications: an example concerning viewshed analysis. *Journal of Archaeological Science*, **25**, 27–38.

Lee, J., and Stucky, D., 1998, On applying viewshed analysis for determining least-cost-paths on Digital Elevation Models. *International Journal of Geographic Information Systems*, **12**, 891–905.

Llobera, M., 1996, Exploring the topography of mind: GIS, landscape archaeology and social theory. *Antiquity*, **70**, 612–622.

Llobera, M., 1999, Landscapes of Experiences in Stone: Notes on a Humanistic Use of a GIS to Study Ancient Landscapes. Unpublished DPhil Thesis, Oxford: Oxford University.

Llobera, M., 2001, Building past landscape perception. Understanding topographic prominence. *Journal of Archaeological Science*, **25**, 1005–1014.

Llobera, M., in press, The nature of everyday experience: examples on the study of visual space. In *Re-Presenting GIS*, edited by D. Unwin (London: John Wiley & Sons).

Miller, R. D., Morrice, J., Horne, P., and Aspinall, R., 1994, Characterization of landscape views. *EGIS 1994 Proceedings*, 223–232.

O'Sullivan, D., and Turner, A., 2001, Visibility graphs and landscape visibility analysis. *International Journal of Geographic Information Science*, **15**, 221–237.

Tandy, C. R. V., 1967, The isovist method of landscape survey. In *Methods of Landscape Analysis*, edited H. C. Murray (London: Landscape Research Group).

Thomas, J., 1993, The politics of vision and the archaeologies of landscape. In *Landscape: Politics and Perspectives*, edited B. Bender (Oxford: Berg), pp. 19–48.

Tilley, C., 1994, *The Phenomenology of Landscape* (Oxford: Berg).

Tomlin, D. C., 1990, *Geographic Information Systems and Cartographic Modeling* (New Jersey: Prentice-Hall).

Travis, M. R., Elsner, G. H., Iverson, W. D., and Johnson, C. G., 1975, VIEWIT: Computation of seen areas, slope, and aspect for land use planning, General Technical Report PSW 11/1975, Forest Service, US Department of Agriculture.

Turner, A., Doxa, M., O'Sullivan, D., and Penn, A., 2001, From isovists to visibility graphs: a methodology for the analysis of architectural space. *Environment and Planning B*, **28**, 103–121.

Wheatley, D., 1995, Cumulative viewshed analysis: a GIS-based method for investigating intervisibility, and its archaeological application. *Archaeology and Geographic Information Systems: A European Perspective*, edited by G. Lock and Z. Stančič (London: Taylor and Francis), pp. 171–186.

Wood, J. D., 1996, The Geomorphological Characterisation of Digital Elevation Models. Unpublished PhD Thesis. Leicester: University of Leicester.