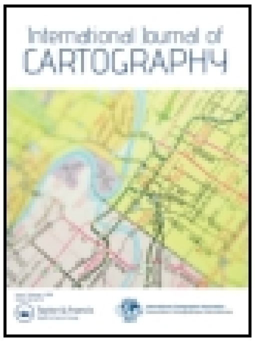

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The effect of topography and elevation on viewsheds in mountain landscapes using geovisualization

Loukas-Moysis Misthos [a,b], Byron Nakos [a], Vassilios Krassanakis [a,c] and Maria Menegaki [b]

[a]School of Rural and Surveying Engineering, National Technical University of Athens, Zographos, Greece; [b]School of Mining and Metallurgical Engineering, National Technical University of Athens, Zographos, Greece; [c]Department of Surveying and Geoinformatics Engineering, University of West Attica, Athens, Greece

ABSTRACT

Visibility analyses provide an opportunity for addressing landscape exploration (e.g. assessing touristic experience). The locations of observers in 3D space and the topographic character of the overall landscape have been shown to act on the respective visibility spatial patterns (viewsheds). However, the way observers explore a landscape is not static but sequential. In this paper, we design explorative geographic visualizations (animated viewshed maps) which dynamically visualize the parts of a mountain landscape that are visible from hypothetical observers moving upon different topographic features (e.g. ridgelines). In these geovisualizations, the observers' elevation changes are displayed with inset profile graphs as well. Overall, these animated maps facilitate the visual exploration of viewsheds' evolution simultaneously with observers' changing positions. In this manner, insight is provided about the influence of the moving observers' topographic features and elevation upon the viewsheds' extent and configuration in a direct visual means. This qualitative approach is complemented by a statistical evaluation increasing the robustness of the results. It turns out that elevation per se is not such a crucial determinant for visibility, and topographic features should be encompassed in an attempt for further quantification and standardization of the way in which mountain landscapes are dynamically experienced.

RÉSUMÉ

Les analyses de la visibilité offrent une opportunité pour faciliter l'exploration des paysages (par exemple l'évaluation des expériences touristiques). La localisation des observateurs dans un espace 3D et le caractère topographique de l'ensemble du paysage ont été identifiés comme des points clés pour la visibilité des structures spatiales (vues). Pourtant la façon dont les observateurs explorent un paysage n'est pas statique mais séquentielle. Dans ce papier nous concevons des visualisations géographiques exploratrices (des cartes de vues animées) qui visualisent de façon dynamique la partie d'un paysage de montagne qui est visible à partir de positions hypothétiques d'observateurs se déplaçant sur différentes entités topographiques (par exemple une ligne de crête). Dans ces géovisualisations, les

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CONTACT Loukas-Moysis Misthos ✉ lmisthos@central.ntua.gr

changements d'altitude des observateurs sont également affichés dans un graphique de profil en encart. Dans l'ensemble, ces cartes animées facilitent l'exploration visuelle de l'évolution des vues simultanément avec le changement de position des observateurs. De cette façon nous proposons un aperçu visuel direct de l'influence du déplacement de l'altitude des observateurs et des entités topographiques sur l'étendue et la configuration des vues. Cette approche qualitative est complétée par une évaluation statistique qui augmente la robustesse des résultats. Il s'avère que l'altitude en tant que telle n'est pas un déterminant crucial de la visibilité, et que les entités topographiques doivent être inclues pour une meilleure quantification et standardisation de la manière dont les paysages de montagne sont dynamiquement expérimentés.

Περίληψη

Οι αναλύσεις ορατότητας παρέχουν την ευκαιρία διερεύνησης/ εξερεύνησης του τοπίου (λ.χ. αποτίμηση της τουριστικής εμπειρίας). Έχει καταδειχθεί ότι οι θέσεις των παρατηρητών στον τρισδιάστατο χώρο και ο τοπογραφικός χαρακτήρας του συνολικού τοπίου επενεργούν επί των αντίστοιχων χωρικών μοτίβων ορατότητας (πεδίων ορατότητας). Ωστόσο, ο τρόπος με τον οποίο οι παρατηρητές εξερευνούν ένα τοπίο δεν είναι στατικός αλλά δυναμικός. Σε αυτό το άρθρο, σχεδιάζουμε εξερευνητικές/ διερευνητικές γεωγραφικές οπτικοποιήσεις (χάρτες ορατότητας κινούμενης εικόνας) οι οποίες οπτικοποιούν τα τμήματα ενός ορεινού τοπίου που είναι ορατά από υποθετικούς παρατηρητές, κινούμενων κατά μήκος διαφορετικών τοπογραφικών στοιχείων (λ.χ. κορυφογραμμές). Σε αυτές τις οπτικοποιήσεις, οι μεταβολές στο υψόμετρο των παρατηρητών παρουσιάζονται κι αυτές μέσω ένθετων τοπογραφικών τομών. Στο σύνολό τους, αυτοί οι χάρτες κινούμενης εικόνας διευκολύνουν την οπτική εξερεύνηση της «εξέλιξης» των πεδίων ορατότητας ταυτόχρονα με τις μεταβαλλόμενες θέσεις των παρατηρητών. Κατ' αυτόν τον τρόπο, παρέχεται βαθύτερη κατανόηση για την επίδραση των τοπογραφικών στοιχείων και του υψομέτρου των παρατηρητών επί της έκτασης και της διάταξης των πεδίων ορατότητας με έναν άμεσο οπτικό τρόπο. Αυτή η ποιοτική προσέγγιση συμπληρώνεται από μια στατιστική αποτίμηση μέσω της οποίας αυξάνεται η στιβαρότητα των αποτελεσμάτων. Τελικά, προκύπτει ότι το υψόμετρο καθαυτό δε συνιστά έναν τόσο κρίσιμο παράγοντα για την ορατότητα, και ότι τα τοπογραφικά στοιχεία πρέπει να εντάσσονται προς την κατεύθυνση της περεταίρω ποσοτικοποίησης και προτυποποίησης του δυναμικού τρόπου με τον οποίο γίνονται αντιληπτά (βιώνονται) τα ορεινά τοπία.

1. Introduction

The experience of landscape is crucial to the human lives' quality and an indispensable component for the thriving of several activities such as tourism (Brabyn, 2015). Moreover, the description of a landscape or terrain regarding its visual structure and properties (i.e. visualscape) is a matter of considerable significance for such experience (see Llobera, 2003; Llobera, Wheatley, Steele, Cox, & Parchment, 2010). On the other hand, '[t]he landscape (visual) experience while walking tracks' (i.e. landscape exploration) differs from the static landscape experience in that it 'has many different permutations' (Brabyn, 2015, p. 210). If this exploration is to take place in unfamiliar (e.g. inaccessible) landscapes and in an automated means, some tools are needed to digitally visualize both the parts of a landscape that are visible and the information related to the topographic character of each landscape.

In the last two decades, terrain visibility (viewshed) has been a standard GIS operation and a topographic derivative in digital terrain modeling to analyze, interpret and visualize the landscape (e.g. De Berg, 1997; De Floriani, Marzano, & Puppo, 1994; De Floriani & Magillo, 1997, 1999, 2003; Fisher, 1993, 1996; Lee, 1991; Nagy, 1994;). Viewshed analyses enable both the delineation of earth surfaces (i.e. regions) that are (not) visible from one or more observation locations (i.e. viewpoints), and – due to the intervisibility principle – the identification of the viewpoints from which certain regions are visible (Klouček, Lagner, & Šímová, 2015).

Viewsheds' geospatial information involves both the regions that are observable in a landscape and the linkage of these regions with the specific locations (viewpoints) from which the former are observable. Hence, viewsheds are in some respects surface parameters dependent upon the local topography (of the viewpoints). In some other, they are non-local (i.e. regional) parameters (Florinsky, 1998; Nutsford, Reitsma, Pearson, & Kingham, 2015; Olaya, 2009; Wilson, 2012) since they 'rely on the terrain shape of a larger, non-neighbor area and need to be defined with reference to other non-local points' (Wilson, 2012, p. 114). Overall, viewsheds represent spatial configurations inextricably linked to their respective viewpoints and, hence, are rated as *perspective-based parameters*. Intuition dictates that visibility is conditioned by viewpoint elevation; yet, research studies have shown that viewpoint elevation is not the sole determinant for terrain visibility (Franklin & Ray, 1994; Lee, 1994). Thus, further experimentation is required in this field, and especially with regards to landscape exploration.

Other factors influencing viewsheds (than topographic ones) can be related to the Digital Terrain Model's (DTM's)/ Digital Elevation Model's (DEM's) scale/spatial resolution. Spatial resolution can play a significant role in determining/ computing local land-surface parameters (e.g. Deng, Wilson, & Bauer, 2007; Evans, 2012; Kienzle, 2004). Even if improper spatial resolution causes a DEM to omit or alter 'some terrain feature that profoundly impacts a viewshed' (Riggs & Dean, 2007, p. 177) the specific way that resolution affects viewsheds is not established. Riggs and Dean (2007) have experimented in computing viewsheds at different resolutions (1, 4, 8, 10, 12, 16, 20 m) and with the aid of different GIS software packages (i.e. quite different viewshed algorithms), and then have compared all of these combinations to the actually (*in situ*) delineated viewsheds. Of all the combinations, the 4-m resolution DEM demonstrated the highest agreement (always greater than 83%). This resolution is not to be deemed as the optimal for every case of viewshed delineation, since it is an *ad hoc* approach valid for a specific landscape or type of land surfaces. It can be deduced, though, that the most refined available resolution is not by all means the one approximating in more realistic terms the actual visible regions.

Exploration of a landscape requires large amounts of such visibility information because it depends on a multitude of viewpoints. This exploration need not always be implemented for the totality of the cells-viewpoints[1] of a DEM representing a landscape. Aside from the increased computational demands this complete description entails,[2] it has been demonstrated by several researchers that some topographic features can be harnessed to adequately sample a terrain/ landscape (Li, Zhu, & Gold, 2005; Peucker & Douglas, 1975; Pfaltz, 1976; Warntz, 1966) or to optimally describe it, in terms of visibility (Kim, Rana, & Wise, 2004; Lee, 1994; O'Sullivan & Turner, 2001; Rana, 2003). More specifically, the 'placement' of viewpoints upon prominent topographic features such as peaks, sinks and passes, and upon their linear counterparts such as ridgelines and courselines seems to have some interesting ramifications on viewsheds, while some kind of routes, such as walking or bicycle trails, is situated upon such features due to reasons of convenience or esthetic landscape experience. Besides, several research papers have shown that the daily traffic of trails is positively correlated with the openness and greenness of trail viewsheds (Lindsey, Han, Wilson, & Yang, 2006; Lindsey, Wilson, Anne Yang, & Alexa, 2008; Wilson, Lindsey, & Liu, 2008).

Given the significance and the permutations of landscape exploration, and the unique character of viewsheds in geomorphological terms, it is worth investigating how viewpoints' occurrences and movements upon prominent topographic features shape visibility patterns. Towards this end, it is useful to find a means of testing this influence. Animated maps have already been developed towards the geovisualization of the dynamic evolution of viewsheds from moving observers, while several parameters for sampling viewpoints in routes of prominent topographic features have been investigated (Misthos et al., 2014). Lonergan, Hedley, and Clague (2015) have also created dynamic visualizations pairing route vision profiles with moment-to-moment information on hazard zone location and tsunami evacuation sign visibility. In this manner, they give a sense of the relationship between various characteristics of the landscape and signage visibility for assessing evacuation potential.

The geovisualization of changing geospatial patterns can be attained through both interactive and animated maps (e.g. Griffin, MacEachren, Hardisty, Steiner, & Li, 2006; Kraak & Ormeling, 2011; Lobben, 2003 MacEachren, 1994; Slocum, McMaster, Kessler, & Howard, 2009). The supremacy of interactivity (i.e. user-control) in terms of usefulness and effectiveness has been extensively discussed (e.g. Cartwright et al., 2001; Cartwright & Peterson, 2007; Dykes, MacEachren, & Kraak, 2005; Harrower, 2007; Koussoulakou & Kraak, 1992; Peterson, 1995). As Cartwright and Peterson (2007, p. 2) put it, increasing levels of interaction/interactivity enhance the attractiveness of maps and augment their functionality, since users are capable of delving at a 'deeper level' of spatial information interrelation/exploration by putting 'the pieces of information together themselves'. A single animation pace in perplex changing maps with no available controls is bewildering for the map-users: for some of them the map plays too quickly, for some others too slowly (Monmonier & Gluck, 1994).

Whereas interactivity entails user-controls, facilitating exploration (Dorling & Openshaw, 1992; Harrower, 2007), animation typically implicates a pre-defined sequence of scenes (Harrower, 2003) in which these controls are minimized. Several authors have exhibited the superiority of animated sequences and maps (over static ones) in 'conveying more information' and in facilitating effective/successful information and knowledge elicitation due to their enhanced potential to visualize 'micro-steps' between larger changes (Blok, 2005; Morrison, Tversky, & Betrancourt, 2000; Patton & Cammack, 1996; Slocum, Robeson, & Egbert, 1990; Tversky, Morrison, & Betrancourt, 2002). These positive effects for learning and insight gaining potentially vanish when user-control is available to an animation, since, for instance, the majority of the participants-users tend to examine still frames by stopping the animation. So, the way animations are designed by generating intermediate frames through techniques of gradual transition such as fade, morph or 'tween' (Battersby & Goldsberry, 2010; Ehlschlaeger, Shortridge, & Goodchild, 1997; Fabrikant & Goldsberry, 2005) enable them to accomplish more than merely a 'successive summation' of their separate display pieces (i.e. key-frames) (Harrower & Fabrikant, 2008). By this 'sequencing', 'the cartographer can increase the likelihood that the reader will notice important features or events in the animation' (Harrower, 2003, pp. 63–64) 'to gain insight from ordered […] spatial data' (Rana & Dykes, 2003, p. 126).

For the geovisualization of the changing viewsheds from topographically prominent routes, animated – and not interactive – maps where opted. Exploring the permutation of the visibility geospatial patterns along routes requires the visualization of a continuous succession of viewsheds from a multitude of pre-defined viewpoints. Such geovizualizations are not compatible with the availability of user-control, but are utterly compatible with pre-ordered sequencing. In this respect, their generation is connected to automation procedures: all the viewshed displays serving as key-frames should be automatically computed and then be transformed in animated maps.

In this paper, we utilize animated viewshed geovisualizations based on a previous research study (Misthos et al., 2014) to visually explore the association between the changing topography of moving viewpoints and their visibility patterns' variations in a meaningful way. In this context, the overarching research goal of the paper is twofold: (i) to reveal how viewsheds vary with observers' horizontal and vertical displacements along specific topographically prominent routes (viewroutes); (ii) to interpret and communicate this co-variation by resorting to geovisualizations' visual exploration and statistical analyses. Techniques such as the insertion of topographic cross-sections (profiles), and practices of understanding space–time patterns *through creating* and by integrating the iterative 'seeing that' and 'reasoning why' phases of exploration (Dorling & Openshaw, 1992; MacEachren, 1995) enable the more general success of the process of geovisualizing (Figure 1). The robustness of the geovisualization results is increased by means of statistical analyses (Figure 1).

2. Materials and methods

2.1. Geographic information processing and analysis

The main input for our explorative geovisualization was a reliable and fine-grained DEM of a landscape including a variety of distinguishable topographic features – ridges, valleys and passes – without at the same time demonstrating extreme roughness. Such a mountain landscape was found in Wyoming, USA. The study area is a 25-km^2 rectangular one, situated within the Teton Conservation District, approximately 15 km SSW off the town of Jackson (Wyoming). The respective 4-m rectangular DEM, representing only the underlying topographic relief (and not the vegetation cover), was downloaded freely from the NSF Open Topography portal (2013) (Figure 2). The DEM was generated in the platform of Open Topography (2013) via a local binning algorithm (Local Gridding) utilizing the elevation information from LiDAR returns contained within a search radius defined by the user. The options/values for the DEM generation were initially set to the default;

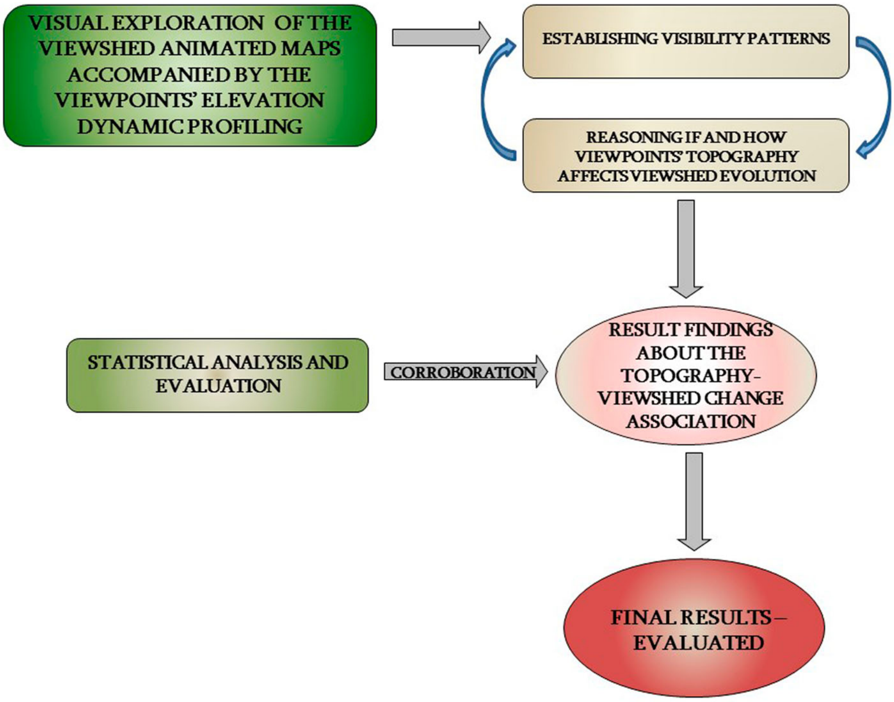

Figure 1. Iterative 'seeing that' and 'reasoning why' stages in visual explorative geovisualization and the contribution of statistical analyses in quantitatively corroborating the visual exploration.

afterwards, the DEM's cell size was resampled to 4 m (from 1 m) by using cubic convolution interpolation in ArcGIS.

The DEM transformation process (12th NAD Zone) and the viewshed analyses were performed using typical functions of the ArcGIS (ESRI®) software. The multiple viewsheds were computed in a semi-automated manner (viewing angles: 360° for the horizontal and 180° for the vertical angle, observer offset: 1 (m), surface offset: 0 (m)). More specifically, three separate routes were engraved along the three selected linear topographic features (Figure 3) and were digitized semi-automatically as nine polylines using the 'streaming digitization mode' under three different spacing intervals of 40, 20 and 10 m. From these nine polyline features' vertices, the respective viewpoints were derived and viewshed analyses were implemented in the ArcGIS' ModelBuilder environment by converting the vertices of each polyline into successive viewpoints. In this manner, viewsheds' digital files were computed consecutively – from each successive vertex-viewpoint.

2.2. Frame processing and geovisualization creation

The next step involves the integration of the viewpoints and viewsheds in animated maps, using the methodology described by Misthos et al. (2014). Each key-frame of these animations was designed in the open source software GIMP (GNU Image Manipulation Program) appropriate for image analysis and three triads of animated viewshed sequences (geovisualizations) were created applying morphing techniques (Morph-WARP Window). For each one of the selected routes, three sequences have been produced by utilizing the

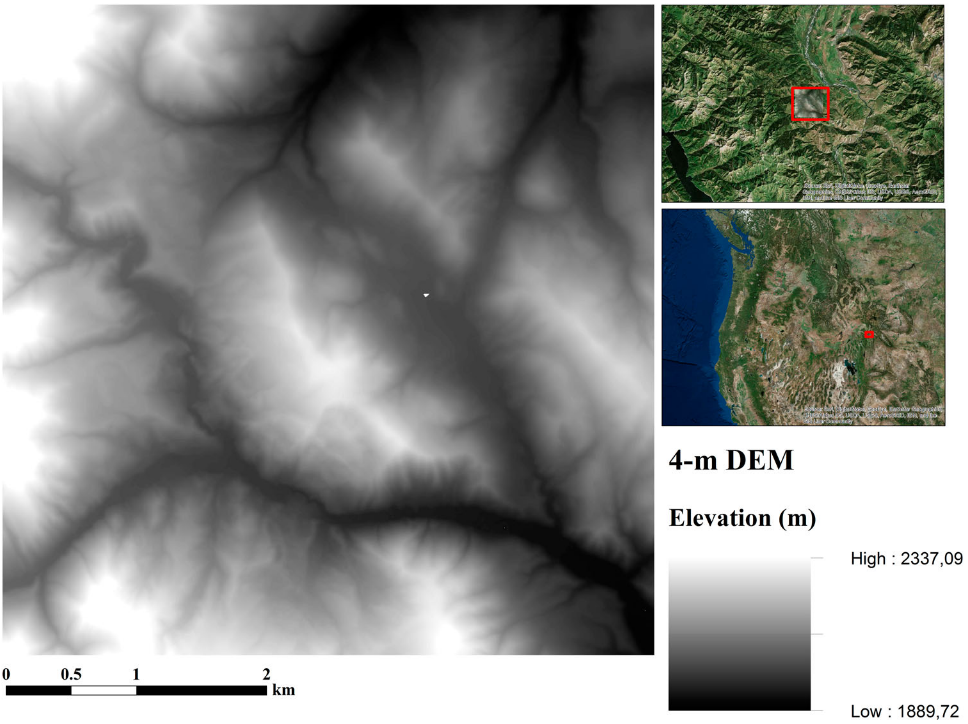

Figure 2. The 4-m resolution DEM of the study area: elevation is visualized through a continuous grayscale color ramp.

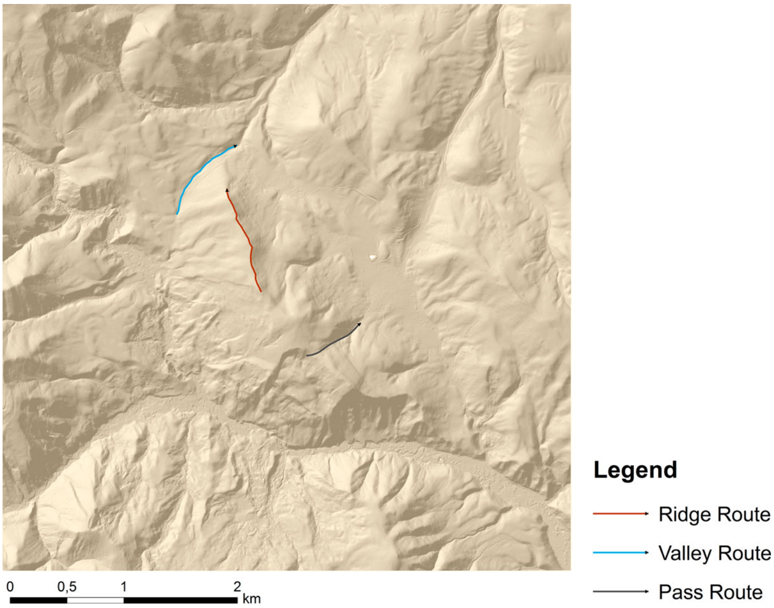

Figure 3. The three viewroutes upon a ridge, a valley and a pass linear topographic feature that were selected for the visual exploration of the dynamically changing animated viewsheds. The routes involve directionality, i.e. direction of locomotion along the route, represented by an arrow at their end.

three viewpoint spacing intervals, aiming at the selection of the most effective geovisualization for each route. The selection was made on the basis of both visual exploration of the geovisualization and calculation/assessment of a quasi-spatial index – Dynamic Coherence Visibility Index (DCVI) (see Misthos et al., 2014).[3] Under this perspective, the most effective geovisualization for each route was selected in terms of its frame coherence and best approximation of the viewsheds evolution in topographically different routes.

The optimal (in terms of effective communication) viewshed geovisualizations were further harnessed for our main explorative task. Since elevation is a significant – albeit not a determining – factor (Franklin & Ray, 1994; Lee, 1994), there was need to visually associate the vertical location of the observers with the viewsheds' evolving. Viewshed animated maps are 2D, so viewpoints' planimetric displacements were easily portrayed. In contrast, changes in the observers' elevation required a topographic cross-section for their visualization. A series of such topographic profiles were plotted, the number of which equaled with the different viewpoints on each route (viewroute), while the position of each viewpoint was distinctively depicted (red circle) against the profile curve (Figures 4 (a–c)). By implementing morphing animation techniques in the image analysis software for both the main display (visualization of the visible/ not visible regions on a hillshaded relief for each viewpoint) and the inset profile graph frames (Figure 5), according to the appropriate specifications (spacing intervals, time delay, etc.) suggested by Misthos et al. (2014), three geovisualizations occurred – one for each viewroute.

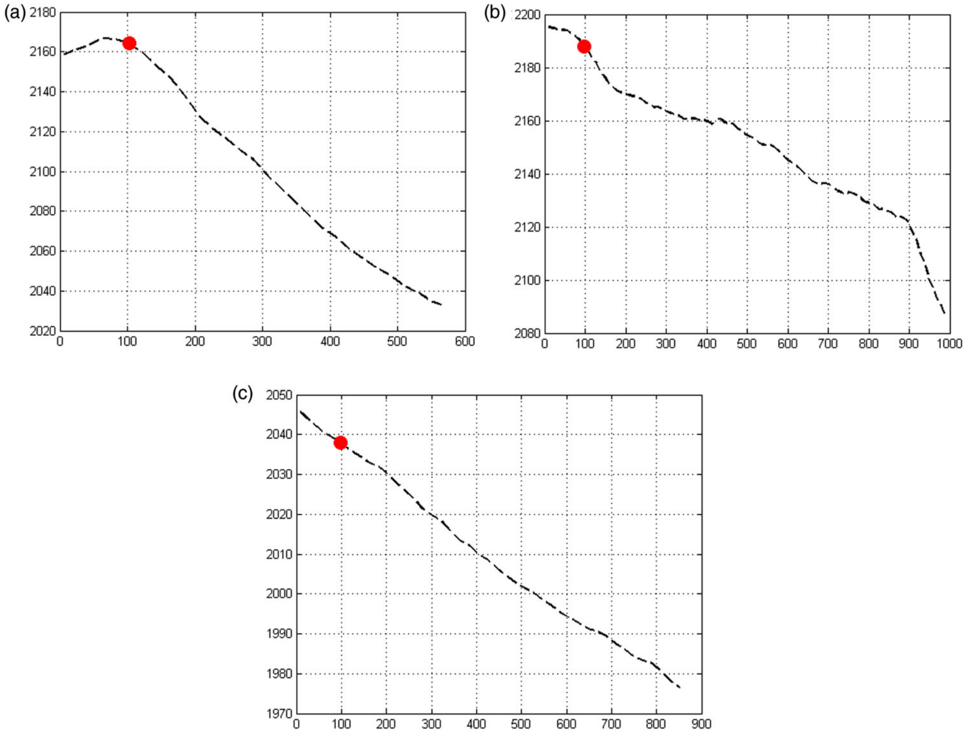

Figure 4. Topographic cross-section frames depicting the position of the viewpoint (red circle) on each viewroute: pass route (a); ridge route (b); valley route (c). The horizontal axis represents length (m), whereas the vertical one represents elevation (m).

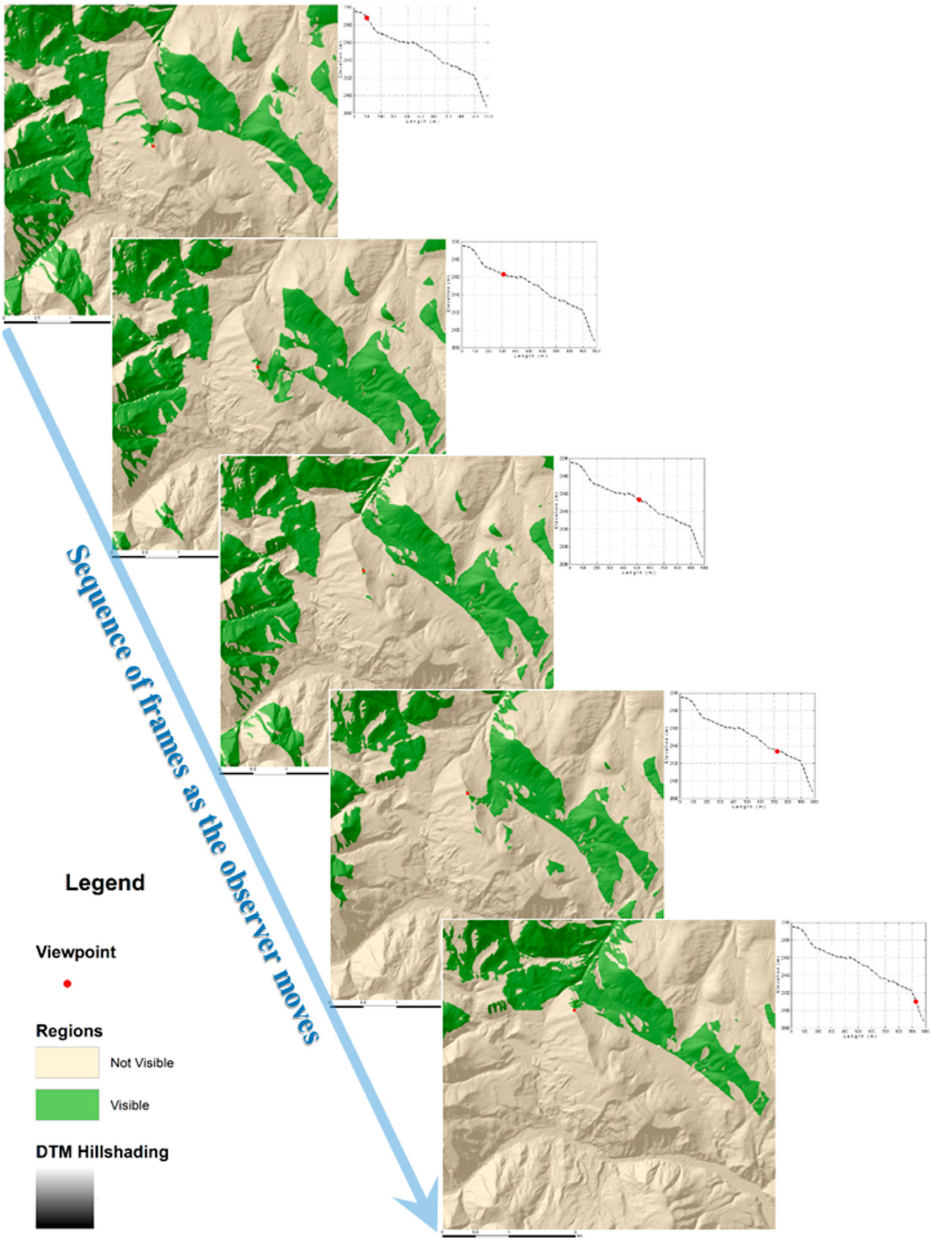

Figure 5. Example of five non-consecutive frames (ridge viewroute geovisualization) used for the animated sequence creation in GIMP.

2.3. Statistical analysis' theoretical considerations

Visual explorations of geovisualizations should be combined with statistical analyses and techniques (Blok, 2005) for reasons of corroboration. In this paper, such analyses were conducted for exploring the association between (i) the *Dynamic Visibility Index* (DVI) – an index presenting the ratio of the number of visible cells for each of the successive viewpoints to the total number of cells of the DEM – and (ii) the topographic feature and elevation of the viewpoint.

Towards this end, some descriptive statistics (minimum, maximum, mean and standard deviation) regarding the elevation and DVI for each of the geovisualizations (i.e. per topographic feature and viewpoint spacing interval) were calculated. Moreover, bivariate analysis was also applied on the observation sample. For such an analysis, normality tests were executed. More specifically, since the exploration is carried out with relation to the three topographic linear features and their three sets of vertex-viewpoint spacing intervals, the normality of all the sub-samples was examined. As it emerged from normality tests (*Kolmogorov–Smirnov* and *Shapiro–Wilk*), for the majority of the sub-groups and variables (Table 1) and from the visual inspection of their histograms and P–P Plots, their respective distributions deviate significantly from the normal ones.

Additionally, aside from normality, the independence of data is another important assumption to be examined (Field, 2009). When implementing analyses on varying spacing intervals, there is a repetition of observations. For instance, the 10-m viewpoint interval viewroutes contain the totality of the observations present in the 20-m and 40-m viewroutes. Thus, both the 40-m and the 20-m viewpoints are subsets of the 10-m viewpoints. As a consequence, when the bivariate statistical analysis is implemented without distinguishing the spacing interval, the independence assumption is violated. So, the fact that the related (non-independent) observations are members of samples of different size (i.e. sets and subsets) signifies that they cannot be subjected to a non-parametric *ANOVA* test, either for independent samples (*Kruskal–Wallis* test) or for related samples (*Friedman* test), unless the test is conducted per spacing interval.

Bivariate analyses were also employed to find a relationship between the visibility (DVI) and the terrain morphology (viewpoints' topographic feature or elevation). Granted that

Table 1. Tests of normality.

			Kolmogorov–Smirnov[a]			Shapiro–Wilk		
Topo feature/viewroute	Space interval		Statistic	df	Sig.	Statistic	df	Sig.
Pass	40 m	Elevation (m)	0.128	13	.200*	0.928	13	0.320
		DVI (%)	0.191	13	.200*	0.900	13	0.134
	20 m	Elevation (m)	0.119	27	.200*	0.916	27	0.032
		DVI (%)	0.162	27	0.068	0.907	27	0.019
	10 m	Elevation (m)	0.114	55	0.072	0.911	55	0.001
		DVI (%)	0.156	55	0.002	0.880	55	0.000
Ridge	40 m	Elevation (m)	0.100	23	.200*	0.986	23	0.979
		DVI (%)	0.100	23	.200*	0.962	23	0.495
	20 m	Elevation (m)	0.087	47	.200*	0.980	47	0.601
		DVI (%)	0.060	47	.200*	0.972	47	0.312
	10 m	Elevation (m)	0.092	95	0.045	0.977	95	0.098
		DVI (%)	0.056	95	.200*	0.975	95	0.063
Valley	40 m	Elevation (m)	0.096	20	.200*	0.947	20	0.321
		DVI (%)	0.227	20	0.008	0.900	20	0.041
	20 m	Elevation (m)	0.087	41	.200*	0.944	41	0.045
		DVI (%)	0.195	41	0.000	0.901	41	0.002
	10 m	Elevation (m)	0.085	83	.200*	0.944	83	0.001
		DVI (%)	0.190	83	0.000	0.902	83	0.000

*This is a lower bound of the true significance.

[a] Lilliefors Significance Correction.

visibility cannot be a determinant of the terrain morphology, DVI was deemed to be the dependent variable. Therefore, in order to specify the influence of the different topographic feature (nominal scale data) on DVI (interval scale data), the Kruskal–Wallis test was employed per spacing interval: since the data are dependent (structured in sets and subsets), comparisons can occur only within the same interval.

Spearman's correlation coefficient was used in the search of a standardized measure of the strength of interrelation between elevation (ratio scale data) and visibility (ratio scale data). Even if this correlation coefficient suggests association and not causation, visibility cannot be deemed the independent variable. In any case, the correlation between elevation and DVI was examined either without distinguishing among different topographic feature types or by enabling this distinction.

3. Results

3.1. Findings from geovisualizations

The effect of viewpoints' topography on the evolution of viewsheds is explored through these three geovisualizations (Videos 1a, 1b, 1c). The results from the visual exploration are summarized per viewroute.

[Videos 1a, 1b, 1c:

Video 1a: https://youtu.be/84smwhYqC20
Video 1b: https://youtu.be/i1X5fLgr-Kw
Video 1c: https://youtu.be/yNcFKo3Jr9w].

3.1.1. Pass route (Video 1a)

This viewroute involves one conspicuous peculiarity with regard to its cross-section: there is a convex segment along the route (at the beginning) at the slope values swing from positive to negative. The slope (s) is defined as: $s = \Delta_{elev}/\Delta_{dist}$, where Δ_{elev} represents the elevation differences in the vertical dimension and Δ_{dist} the distance differences in the horizontal dimension of the profile. More precisely, at the first steps of the animation, the moving viewpoint proceeds upwards, and then, quickly, turns downwards. At this critical segment, the animation is accompanied by a major shift in the respective viewsheds. When the observer reaches the pass point (where slope and curvature are locally zero), both sides along the direction of locomotion can be visible, but by the moment this point has been overcome, visibility is permitted only towards the direction of the observer's movement. After that, the viewpoint continues to move from greater elevations to lower ones. Overall, the generally moderate elevation and slope variations of the profile curve within the pass route produce fan-shaped viewshed patterns gently modified for the most of the duration of the rest of the animation (after the change of slope sign). Visibility tends to dwindle with elevation decrease, but a little before the end of the route – even if the viewpoint keeps on moving downwards – visibility rises again. This is due to the fact that the viewpoint eventually 'finds an opening' from the otherwise confined pass route at the end; as a result, the fan-shaped viewsheds are becoming more flattened and widened.

3.1.2. Ridge route (Video 1b)

The topographic profile of the ridgeline exhibits a jagged form, and, although the generic trend of locomotion takes place apparently from higher elevations to lower ones, at some points this trend is locally inversed, since there are some cusps or 'stairs'. From a cross-section perspective, this route could be partitioned into some topographically homogeneous segments, occurring along the route, namely: (a) the 0–180-m relatively steep concave-profile, (b) the 180–340-m gentle straight-profile, (c) the 340–750-m 'terraced' profile, (d) the 750–900-m mild straight-profile and (e) the 910–990-m steep straight-profile.[4] It is worth noticing that we have presumed that elevation and its variations significantly impinge on viewsheds. Therefore, in order not to be biased, we had initially fixated our attention to the main geovisualization display and, subsequently, we identified the segments (on the profile) for which extreme fluctuations happen. From this independent 'visualscape' exploration tactic, four 'discrete' cases where the viewshed patterns are fundamentally altered were spotted: (i) the most abrupt changes emerge at the route segment between 380 and 430 m, while (ii) a sequence of very swift visible regions' supersessions (at relatively adjacent locations) are clearly discernible at about 550 m; (iii) the 680–750-m section presents a major 'amount' of viewshed fluctuation and (iv) a less significant series of variations take place along the penultimate (d) part of the route (800–900 m). By carefully inspecting the profile for these cases (segments/ points), it can be inferred that the presence of successive local minima/local maxima bring about significant viewshed sudden shifts. In other words, the alternation between convex/concave curve segments and the changing values and signs of slopes greatly affect the viewshed evolution (also see Pass Route section) both quantitatively (i.e. number of visible cells) and geographically (i.e. spatial distributions). This seems to be a rather conclusive evidence, as far as almost the totality of the 'violent' changes take place within the c route segment. But segment d also contains two inconspicuous yet sharp cusps, and the 'jumpy' viewshed shifts do coincide with these slope transitions. On the other hand, segments a, b and e are characterized by a hypsometrically strictly decreasing sequence. An equally important remark is that from all these three segments, the most coherent one – in terms of visibility evolution – is e, albeit it entails the highest elevation changes. This finding appears to signify that even though visibility values co-vary with elevation values, local elevation and, mostly, slope changes (i.e. cusps) account for high and erratic viewshed twists.

3.1.3. Valley route (Video 1c)

The profile graph for this route differs from the other two considering that it does not present prominent irregularities, and when some micro-bulges protrude in this gentle curve slope ($\approx$9% mean slope) they comprise neither absolute, nor local maxima elevation points. Such a typical – almost 'featureless' – route segment exists between 400 and 600 m. Along this segment, visualscape variations are very low, and mostly between 400 and 500 m, where visible cells exist mainly within the valley's surroundings. On the other hand, the most conspicuous viewshed spatial transitions take effect at 170–230, 300–400 and 600–700 m; but it is at these specific points/segments that the subtle slope modifications emerge. And, in spite of the slight visible region variations in absolute figures, their relative transitions are indeed very intense, due to the overall very low visibility values. Whenever a significant spatial (and numerical) alteration occurs, it is linked to a slope modification. In addition, another peculiarity characterizing this viewroute is that whereas elevations constantly decline along the valley route, viewsheds do not; instead, they tend to increase at the aforementioned segments. Therefore, it could be reckoned that even if no higher grounds are present (as in pass's and ridge's cusps), visibility is augmented only because slope changes.

3.2. Statistical evaluation: calculations

3.2.1. Descriptive statistics

Elevation (and its fluctuations) appears to be a factor that significantly modifies viewsheds. However, as it emerges by both the descriptive statistics (Table 2) and the three geovisualizations, the elevation differences among topographic features are not so high. For instance, the maximum elevation of valley viewpoints is only 40 m lesser than the minimum elevation of ridge viewpoints, but their discrepancies in the DVI are almost 23 percentage units; similarly, the mean elevation of pass viewroute (≈2100 m) is hardly 50 m lesser than the mean elevation of the ridge viewroute (≈2150 m) – a difference that cannot by itself explain or justify such enormous disparities in viewsheds (almost 20 percentage units). It emerges, thus, that elevation differences (Δ_{elev}) (as an independent variable) both *within the same* and *among different types* of topographic feature(s) do affect viewsheds, but in radically different manners (i.e. quantitatively and spatially). It should be noted, though, that what numerical figures and statistics can explicitly reveal about the areas of changing visible regions, cannot reflect for the patterns, agglomerations and their spatial 'stories'.

3.2.2. Bivariate statistical analysis

By implementing a Kruskal–Wallis test per spacing interval, the influence of the different topographic feature (nominal scale data) on DVI (interval scale data) is specified. It occurs

Table 2. Descriptive statistics of elevation and DVI for the three topographic features/viewroutes and their optimal viewpoint spacing intervals.

Topographic feature/viewroute	Space interval		*N*	Minimum	Maximum	Mean	Standard deviation
Pass	40 m	Elevation (m)	15	2032.80	2166.25	2103.81	48.36
		DVI (%)	15	3.79	8.96	5.80	1.62
	20 m	**Elevation (m)**	**29**	**2032.80**	**2166.85**	**2104.04**	**47.01**
		DVI (%)	**29**	**3.79**	**10.27**	**5.82**	**1.69**
	10 m	Elevation (m)	57	2032.80	2167.08	2104.26	46.21
		DVI (%)	57	3.76	12.77	5.84	1.80
Ridge	40 m	Elevation (m)	25	2086.52	2195.35	2150.55	27.55
		DVI (%)	25	16.50	36.26	24.80	5.24
	20 m	Elevation (m)	49	2086.52	2195.35	2150.87	26.24
		DVI (%)	49	16.50	36.26	24.94	5.15
	10 m	**Elevation (m)**	**97**	**2086.52**	**2195.35**	**2151.05**	**25.50**
		DVI (%)	**97**	**16.41**	**36.62**	**25.04**	**4.96**
Valley	40 m	Elevation (m)	22	1976.51	2046.32	2010.25	21.84
		DVI (%)	22	0.71	3.90	1.83	0.94
	20 m	**Elevation (m)**	**43**	**1976.51**	**2046.32**	**2010.23**	**21.15**
		DVI (%)	**43**	**0.71**	**3.90**	**1.83**	**0.89**
	10 m	Elevation (m)	85	1976.51	2046.32	2010.23	20.81
		DVI (%)	85	0.71	3.90	1.82	0.87

Notes: Note that the statistics for the opted viewpoint spacing intervals – 20, 10 and 20 m for the pass, ridge and valley viewroutes respectively – are in bold.

Table 3. Mean DVI Ranks – Kruskal–Wallis test – among topographic features per space interval.

Space interval		Topographic feature/viewroute	*N*	Mean rank
40 m	DVI (%)	Pass	15	29.93
		Ridge	25	50.00
		Valley	22	11.55
		Total	62	
20 m	DVI (%)	Pass	29	57.93
		Ridge	49	97.00
		Valley	43	22.05
		Total	121	
10 m	DVI (%)	Pass	57	113.93
		Ridge	97	191.00
		Valley	85	43.05
		Total	239	

that the DVI mean ranks among the three topographic features (for each interval) significantly differ. Irrespectively of the spacing interval, valley viewroutes display the lowest mean ranks and ridge routes the highest mean ranks, whereas pass routes receive intermediate values (Table 3). This is consistent with the results from the descriptive statistics: DVI arithmetic means are ascending from valley viewpoints towards ridge viewpoints. Yet, what bears great importance is the zero value (0.000) of the asymptotic significance value, and the zero value of the *Monte Carlo* estimate of significance (<0.05) (Table 4). On these grounds, we can safely conclude that the type of the topographic feature (independent variable) – i.e. configuration of viewpoints along these different features – genuinely and significantly affects the DVI (viewsheds) (dependent variable). Nonetheless, this test (one-way ANOVA) signifies that a difference exists, but does not inform us exactly where this difference lies (Field, 2009).

Finally, the Spearman's correlation coefficient is used to calculate the quantitative interrelation between elevation (ratio scale data) and DVI. Taking as dependent variable the DVI and by sub-categorizing (grouping) per space interval, the correlation between elevation

Table 4. Test Statistics[a,b] for the validity of the influence of the topographic feature upon the DVI.

		Space interval		DVI (%)
40 m	Chi-square			53.312
	Df			2
	Asymp. Sig.			0.000
	Monte Carlo Sig.	Sig.		0.000[c]
		99% Confidence interval	Lower bound	0.000
			Upper bound	0.000
20 m	Chi-square			104.884
	df			2
	Asymp. Sig.			0.000
	Monte Carlo Sig.	Sig.		0.000[c]
		99% Confidence interval	Lower bound	0.000
			Upper bound	0.000
10 m	Chi-square			208.039
	df			2
	Asymp. Sig.			0.000
	Monte Carlo Sig.	Sig.		0.000[c]
		99% Confidence interval	Lower bound	0.000
			Upper bound	0.000

[a] Kruskal–Wallis test.
[b] Grouping variable: Topographic feature.
[c] Based on 10,000 sampled tables with starting seed 2,000,000.

Table 5. Correlation between elevation and DVI per space interval.

Space interval				DVI (%)
40 m	Spearman's rho	Elevation (m)	Correlation coefficient	0.896**
			Sig. (2-tailed)	0.000
			N	62
20 m	Spearman's rho	Elevation (m)	Correlation coefficient	0.894**
			Sig. (2-tailed)	0.000
			N	121
10 m	Spearman's rho	Elevation (m)	Correlation coefficient	0.893**
			Sig. (2-tailed)	0.000
			N	239

**Correlation is significant at the .01 level (2-tailed).

and DVI is presented either without distinguishing among different topographic feature types (Table 5) or by enabling this distinction (Table 6). When attempting to link elevation with DVI in an aggregate manner, the correlation coefficient is very strong positive at the 0.01 level, regardless of the space interval. When the same relationship is investigated with regard to the differing topographic feature, the correlation turns out to be (very) strong positive for pass and valley viewroutes and moderate positive for the ridge viewroute at the 0.01 level (only for the 40-m ridge the correlation is significant merely at the 0.05 level). The values of the first 'version' (Table 5) are larger than the largest values of the second 'version' (Table 6): for instance, considering the 10-m space interval, as being the most representative sub-sample, and with reference to the pass feature, the pertinent values are 0.893 and 0.880, respectively (very high). This is not surprising since the sample

Table 6. Correlation between elevation and DVI – per space interval and per topographic feature.

Space interval	Topographic feature/viewroute				DVI (%)
40 m	Pass	Spearman's rho	Elevation (m)	Correlation coefficient	0.857**
				Sig. (2-tailed)	0.000
				N	15
	Ridge	Spearman's rho	Elevation (m)	Correlation coefficient	0.471*
				Sig. (2-tailed)	0.018
				N	25
	Valley	Spearman's rho	Elevation (m)	Correlation coefficient	0.809**
				Sig. (2-tailed)	.000
				N	22
20 m	Pass	Spearman's rho	Elevation (m)	Correlation coefficient	0.881**
				Sig. (2-tailed)	.000
				N	29
	Ridge	Spearman's rho	Elevation (m)	Correlation coefficient	0.435**
				Sig. (2-tailed)	0.002
				N	49
	Valley	Spearman's rho	Elevation (m)	Correlation coefficient	0.792**
				Sig. (2-tailed)	0.000
				N	43
10 m	Pass	Spearman's rho	Elevation (m)	Correlation coefficient	0.880**
				Sig. (2-tailed)	0.000
				N	57
	Ridge	Spearman's rho	Elevation (m)	Correlation coefficient	0.416**
				Sig. (2-tailed)	0.000
				N	97
	Valley	Spearman's rho	Elevation (m)	Correlation coefficient	0.785**
				Sig. (2-tailed)	0.000
				N	85

*Correlation is significant at the .05 level (2-tailed).
**Correlation is significant at the .01 level (2-tailed).

in the first version integrates inherently (geomorphologically) different (and thus not dependent/ related data) samples on a more aggregate manner and, therefore, can encompass more diverse cases, ending up in more consistent associations between elevation and DVI. On the other hand, when comparing the correlation coefficients among topographic features with DVI for the 10-m space interval, it appears that their values for the pass (0.880) and the valley route (0.785) are very high and adequately considerably high respectively, while for the ridge this value (0.416) is moderate.

4. Discussion

Understanding visualscapes (e.g. Llobera, 2003; Llobera et al., 2010) by giving emphasis on prominent topographic features has been a concern in the pertinent literature (e.g. Kim et al., 2004; Lee, 1994; O'Sullivan & Turner, 2001). Stucky (1998) and Lu, Zhang, Lv, and Fan (2008) have described and delineated several types of routes in terms of their visibility levels. Besides, the selection of walking routes/ trails has been empirically correlated with the openness and greenness of their viewsheds (Lindsey et al., 2006; Lindsey et al., 2008; Wilson et al., 2008).

In this paper, the dynamic behavior of viewsheds has been explored. Lonergan et al. (2015) investigation of the correlation between various characteristics of the landscape and signage visibility for assessing evacuation potential using dynamic visualizations is an attempt towards this direction. Nevertheless, the exploration of the effect of topography and elevation of moving observers upon viewsheds has been implemented in an explicit manner in this paper. Elevation and elevation differences (of the moving viewpoint) have been found to be significantly correlated with the changing visibility patterns. Moreover, it has emerged that the dynamic visualscapes owe their changing numbers of visible cells not simply to the elevation, but also to the *elevation and slope differences* between successive locations of the moving viewpoint; and these numbers are quantized according to the DEM resolution and the viewpoints' spacing.

Nonetheless, this dynamic interrelation is not developing in a uniform manner. The viewpoints' elevation or slope differences *do not determine DVI regardless of their spatial occurrences*; contrariwise, their influence depends on the (linear) topographic feature where they exist. In other words, it is shown that the topographic features' particularities play a decisive role as well: they shape the range within which elevation variation can act. On the one hand, it generally occurs that as viewpoints' elevation decreases, visibility also declines within each viewroute; on the other hand, the impact of elevation variation on dynamic visualscapes is differentiated across different topographic routes.

The effect of viewpoints' elevation and slope is not the same for the ridge, pass and valley routes. Whereas only a small change of slope is enough to cause a large percentage viewshed transition in valley route, this does not apply to ridge routes as well; for significant viewshed pattern alterations to come about in the ridge route, not only changes in slope, but also changes in the convexity/ concavity are required to be present. These findings are corroborated by the statistical analyses. The pass viewroute's correlation coefficient strongly indicates that as one is moving from lower altitudes to greater ones, the visibility is increased – and something similar applies for the valley route, even though in a somewhat lesser degree; for the ridge viewroute, though, which displays the lowest correlation value, this association is not so straightforward.

Regarding the procedure for exploring viewsheds while assessing the role of topography, it seems that the presence of the dynamic profiling inset potentially distracts attention. However, the *split attention effect* (see Harrower, 2003, 2007; Mayer & Moreno, 2003) (between the main and the inset geovisualization display) can be managed if attention is initially directed only on the main display. Moreover, since the core of the matter of this research study is to explain or interpret the changing visibility patterns based on the varying topography of the moving observer, watching independently these two variables is not only necessary, but it is also desired. After several times of watching the main geovisualization and when the generic trend and specific irregularities have been established, the actions of tracing the respective segments upon the cross-section ensue. At this first 'reading', the 'seeing that' (visible regions in the main display) is being attached to a 'reasoning why' (alterations of topography in the profile display). Yet, in a later stage, a more knowledge-based approach takes place and the focus shifts on the profile display and on these segments that both direct observation and some of our initial hypotheses dictate us to concentrate on. Next, we may once again fixate our gaze to the main display, recapitulate the break-points locations on the cross-section, re-explain and re-assess the influence of topography, and so on. After iteratively exploring the geovisualizations, we can assess whether our initial hypotheses regarding the linear topographic feature's and elevation's effect on viewsheds are sustained. This two-stage cyclical process provides us with information and insight by dynamically imbuing with meaning the evolving spatial data (see Blok, 2005; MacEachren, 1995).

Statistical analyses are implemented to corroborate the findings from the previous cyclical process of visual exploration (Figure 1), albeit in a means that differs in qualitative terms. One should keep in mind that when dealing with numerical (i.e. non-spatial) statistics, the pertinent analysis and interpretation should and could not refer to terms like expansion or shrinkage which bear spatial reference. If one takes into consideration the previous statistical analyses regarding the DVI, he/she may only partially overcome the intrinsic barriers of the understanding and the interpretation of the spatial dynamics. For instance, regarding the 20-m interval pass viewroute, one can only get the information that: (i) its DVI variations are deeply rooted on its 'being a pass route and not another topographic feature'; (ii) the visible covering percentage of the total area fluctuates around the arithmetic mean of its DVI (≈5.8%), being strongly and positively correlated to viewpoint elevation variations: as the moving viewpoint either ascends or descends, the DVI percentage responds in a highly straightforward manner, by either mounting or diminishing respectivelyand (iii) the manner in which these fluctuations occur is adequately coherent (except for a viewpoint-viewshed transition that exhibits a 'break').

Therefore, these numeric figures and the respective correlations and explanations do prompt us understand and statistically test and ground the importance of some factors which impinge on viewsheds and on the consistency of their dynamic transition. Nonetheless, they tell us almost nothing about viewsheds' spatial configuration or about the fashion in which they are spatially and temporally changing. The spatial 'story' of the viewsheds could not be reconstituted or approximated on the basis of these quantitative, numeric data. Only a proper explorative geovisualization can address the dynamic spatial transition of the visibility patterns and enable the existing connection with the topography in an explicit/graphical way – not being intermediated by figures and arithmetic indices.

5. Conclusions

Commencing by the platitude that one has to climb up at higher grounds to be able to see the most of a landscape, observer's elevation appears to be a salient determinant for visibility. As experimentally shown, elevation fluctuations are accompanied by visibility variations: the visual exploration of viewpoints' displacements along topographically prominent viewroutes reveals that viewsheds' dynamic geospatial behavior depends on viewpoints' elevation changes. However, it does not follow from the former that viewsheds issue only from viewpoints' elevation changes. The experimental comparison among different routes evidences that although viewpoints' elevation influences visualscapes' evolution, this evolution significantly deviates from route to route. This means that information of the surrounding terrain latently inhering in prominent topographic features (routes) significantly complements the interpretation of viewsheds' dynamic behavior. Hence, the influential action of elevation cannot but be inquired within the overarching framework of the topographic feature.

Even more expressly, one should consider not only the elevation of the topographic cross-section of each route, but their slope and curvature. It has been shown that the profiles' (1.5D) *slope* and *curvature* variations significantly explain the prominent viewshed transitions – even more definitely than elevation. Yet, while for the pass and ridge viewroutes the changes in slope direction and the transition from convex to concave sub-segments coincide with such major visibility pattern shifts (often both in spatial and quantitative terms), for the valley viewroute even moderate changes in slope induce significant visibility pattern alterations. To sum up, it could be inferred that the topographically different viewroutes do not directly regulate the partial viewshed transition within a route but they delineate the overall trend, while the variations of the terrain profile (elevation, slope and curvature) do affect 'internally' these visualscape shifts.

These associations emerged by employing an effective visualization synthesis. To this end, the insertion of the moving viewpoint topographic profile substantially facilitated the link between the moving viewpoints' elevation (Z) and their dynamic viewsheds (DVI). The particular potency of the dynamic viewpoint elevation profiling lies on the readily-perceivable graphical depiction of the 1.5D morphological status – elevation, slope, curvature – of the route segment; it also lies on the explicit dynamic presentation of the viewpoints' elevation shifts with relation to the viewpoints' horizontal displacements and to the dynamically changing viewsheds on the main display. Eventually, by several visual explorations of the geovisualizations – while consulting the respective statistical values and correlations at the same time (Figure 1) – a better understanding was gained which would be missed if the profile was not incorporated in the visualization.

In any case, though, the insight derived from the animated viewshed maps' visual exploration is not rooted on a rigorously tested theoretic framework with a universal validity. Furthermore, the limited spatial extent of the area (DEM) studied regarding the delimitation of viewsheds raises some concerns. The DEM's extent may cause the misrepresentation of viewsheds' sizes if the regions visible from specific viewpoints near the edge of the DEM lie outside the extents of the DEM (Caldwell, Mineter, Dowers, &

Gittings, 2003). However, in this paper, the viewsheds-frames of the animated sequences do not occur from viewpoints on the edge of the study area (viewponts are located at least 1–1.5 km away from edges. As previously stated, viewsheds are context-specific geomorphological parameters dependent on the wider topography of different landscapes and no standardized norms exist to determine the appropriate landscape (DEM) extent for computing and delineate viewsheds. Overall, this *edge effect* 'does not invalidate the results of analyses made on the viewsheds […], but merely restricts their applicability to the limits of the area covered by the DEM' (Caldwell et al., 2003, n.p.). As a consequence, the explanatory power of these geovisualizations is somewhat limited: extrapolating the current exploration procedure to different landscapes may not be sound. The statistical analyses, as demonstrated above, cannot substitute the visual exploration process taking place in viewsheds geovisualization for revealing 'new' patterns and spatiotemporal associations. Nonetheless, they can increase the robustness of the findings from the previous process in a quasi-spatial, quantitative manner and attribute a probabilistic substantiation to them (Figure 1).

Mountain landscapes provide a proper case for exploring viewshed variations along topographically prominent routes utilizing explorative geovisualization. However, further work needs to be done towards encompassing other landscapes that are geomorhologically distinctive or esthetically sensitive such as volcanic areas, fluvial areas (alluvial fans/ bajadas), mining areas, etc. The design and implementation of such explorative geovisualizations can enable a fruitful comparative analysis.

Notes

1. Such a viewshed implementation refers to the notion of total viewsheds (see Wheatley, 1995; Llobera, 2003).
2. Viewshed implementation on a raster/gridded DEM is relatively challenging due to the high computational complexity: the computation of the complete visibility maps or total viewsheds (i.e. viewsheds from all the points of the terrain) has a complexity which is expressed as $O(N^2)$ where N is the total number of points of the DEM (Tabik, Zapata, & Romero, 2013; Feng et al., 2015).
3. It is worth noticing that these practices are parts of an explorative geovisualization strategy which, contrariwise to its usual role, is not to reveal latent spatiotemporal patterns included in geographic processes (Blok, 2005; Kraak & van de Vlag, 2007). It is rather dedicated to revealing the geovisualizations' 'deficiencies' themselves in a sense analogous to the manner that Ehlschlaeger et al. (1997) have utilized animation at its exploratory dimension, that is to provide added value information about the uncertainty of the data and the way this uncertainty affects the application of concern.
4. Reference to the specific distance values is made only to describe topographically different segments of the profile.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

Loukas-Moysis Misthos is a PhD candidate in the School of Mining and Metallurgical Engineering, National Technical University of Athens, Greece. His main research interests focus on the perception and evaluation of the mining and mountain landscape utilizing geospatial analysis, geovisualization and eye movement analysis.

Byron Nakos is Professor in the School of Rural & Surveying Engineering of the National Technical University of Athens. His research interests are related to cartographic generalization, children and cartography, eye-tracking and cartographic visualization, analytical hill-shading and design and development of spatial information systems applications. He has participated as leader or key researcher to several research projects on cartography and geoinformation funded either by the European Union or by public bodies. He has published his research work through more than one hundred referred papers on scientific journals, conferences proceedings and he is the author or co-author of more than ten books. For several years, he served as the Director of the Cartography Laboratory and Head of the Department of Surveying Engineering at the School of Rural & Surveying Engineering of the National Technical University of Athens. Currently, he is appointed as the President of Board of Directors of the Hellenic Cadastre of Greece.

Dr. ***Vassilios Krassanakis*** holds a Diploma Degree in Rural and Surveying Engineering from National Technical University of Athens (NTUA) and a Doctor of Engineering Degree in Cartography from the same university. His main research focuses on map perception, geovisualization techniques, and geographic information systems. He is an expert in eye movement analysis methods. Vassilios currently serves as Visiting Professor at the Department of Surveying and Geoinformatics Engineering of University of West Attica as well as Postdoctoral Collaborator at NTUA.

Dr. ***Maria Menegaki*** is an Assistant Professor in the School of Mining & Metallurgical Engineering, National Technical University of Athens, Greece. She holds a PhD in Surface Mining and Environment. Her research interests include surface mining planning and design, mining economics and environmental impacts of mining.

ORCID

Loukas-Moysis Misthos http://orcid.org/0000-0002-3244-2546

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