Geovisualization: Multidimensional Exploration of the Territory

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Abstract: The purpose of this position paper is to emphasize the remaining challenges for geovisualization in an evolutive context of data, users and spatio-temporal problems to solve in an interdisciplinary approach. Geovisualization is the visualization of spatio-temporal data, phenomena and dynamics on earth, based on the user interaction with heterogeneous data, and their capacities of perception and cognition. This implies to bring closer together knowledge, concepts and models from related scientific visualization domains, for a better understanding, interpretation and analysis of spatio-temporal phenomena on earth. We currently face and cross several types of complexities, regarding spaces, data, models and tools. Our position here, based on past and on-going works, as first proofs of concept, is to model a multidimensional exploration of the territory, because integrating explorations of uses, styles, interaction and immersion capacities, until various 'points of view' on the represented spatio-temporal phenomenon.

1 INTRODUCTION

The amount of heterogeneous geospatial data, multi-sensors, multi-sources, multi-scales, more or less precise, and more or less massive, motivate the users to visualize them all together, in addition to textual archives, iconographic collections and any possible spatialized information (*co-visualization*). Additionally, the users expect tools offering ways to navigate into all those data, through space and time (*navigation*). For scientific purposes, some users need to detect changes, breaks, and artifacts in data, to compare sources and imprecision, to compare measures in time, simulation, prediction scenarii, or learning models. For general public purposes, characteristics of a spatial issue on earth have to be explained, graphically synthesized and should support collaborative mediation. Those typical user needs require to visualize a spatio-temporal data, phenomenon or dynamics from various possible points of view (*multi-dimension*). Even if cartographic, geovisualization or datavisualization tools exist, no visualization system is now able to offer flexible multi-dimensional visualization of spatio-temporal information, based on the navigation into geospatial ans spatialized data, to ease the visual reasoning on complex spatio-temporal dynamics on earth. Geovisualization is the set of knowledge, methods and tools favoring the visualization and the visual analysis of geographic spaces and spatio-temporal phenomena, based on the user interaction with geographic or spatial data (MacEachren and Kraak, 2001; Dykes et al., 2005).

We would like to emphasize that geovisualization is most of all related to the all methodological approach and the modeled processes of both graphic representation and rendering of, and the interaction with, geospatio-temporal information, enhancing the knowledge inference on geographic spaces and spatial phenomena. The purpose is to "see, perceive and understand", based on the user exploration of data and graphic representations, while preserving what could be meaningful for the users into the represented geographic spaces and phenomena. Similarly to information visualization and data visualization, but geospatial-oriented, geovisualization should facilitate both the exploration of the geospatial data and the first steps of visuo-spatial interpretation. Geovisualization is not only about designing new technologies for co-localized geospatial data visualization, but also about addressing the complexity to visualize a spatio-temporal phenomenon interacting with the related geographic spaces. Through years, the context has evolved from challenges already existing but that have become more pronounced over time. More heterogeneous, imprecise and massive spatial and non-spatial data are available to be combined and hybridized for visualization; a diversity of users expects to visualize complex spatio-temporal phenomena in

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order to see, explain, analyze and understand complex spatial dynamics and systems; finally, user interaction and interfaces allow to investigate innovative modes to explore data and to virtually or in an augmented way experience geographic spaces. Geovisualization is about bringing knowledge, concepts and models for a better understanding, interpretation and analysis of spatio-temporal phenomena on earth. This is an interdisciplinary, and even transdisciplinary field: geovisualization aims at specifying and integrating new models of abstraction, representation, perception and cognition related to geographic spaces, with the help of and contributing to geographic information sciences, HCI, computer graphics and cognitive sciences. In this position paper, we aim at emphasizing and revisiting essential challenges for geovisualization, in specifying how the issue of the visualization of spatio-temporal data could be addressed as a multidimensional exploration problem, based on our own research approach.

2 GEOVISUALIZATION

Geovisualization integrates approaches from ”visualization in scientific computing, cartography, image analysis, information visualization, exploratory data analysis, and geographic information systems to provide theory, methods and tools for visual exploration, analysis, synthesis, and presentation of geospatial data” (MacEachren and Kraak, 2001). It refers both to the science and the techniques to design and use ”visual geospatial displays to explore data and through that exploration to generate hypotheses, develop problem solutions and construct knowledge” (Kraak, 2003). Since, the main trend is still to iterate from the users needs, in order to design and to handle effective geovisualization techniques (Nöllenburg, 2007; Lloyd and Dykes, 2011), and to connect people, maps and processes to acquire knowledge (Dykes et al., 2005). The challenge of enhancing spatial analysis based on visual media is related to *geovisual analytics* (Andrienko and Andrienko, 2005; Keim et al., 2008; Andrienko et al., 2014; MacEachren, 2015), that we consider to be a part and a purpose of our ’geovisualization issue’. This raises issues of interrelated design and use, for geospatial data exploration, based on but also leading to issues of perception and cognition. The main challenges for geovisualization designers is to take into account the set of the following complexities: 1- Geographic spaces and data to handle; 2- Spatio-temporal phenomena and models to represent; 3- Visual integration and interactive or even immersive exploration of data, to design.

Geographic Spaces and Data. A geographic space is characterized by its terrain, landscapes, natural and artificial entities, shapes, volumes, structures and arrangements, modeled into heterogeneous, imprecise and massive spatial data, according to acquisition methods, sources, scales, data types, etc. The description and analysis of geographic spaces and their interaction with other dynamic systems on earth come mainly from geography and geosciences. We face an amount of geospatial data (vector databases, maps, various imagery, 3D models, numeric models, point clouds, etc.) but also non-spatial data (texts, stories, web data, statistic data, photographs, etc.) that can be spatialized. The handling of the suitable scale to manage, while preserving the spatial arrangements of the territory, as having a proper positioning or controlled level of uncertainty of the geolocalization of things are at stake here. Graphically representing these geographic spaces and phenomena requires to preserve spatial coherence of the information, related to their geometry, topology and semantic, while preserving their structure and their meaning. Visual perception and spatial cognition play a great role there to drive representation choices. Massive geospatial data bring us also to go closer to image rendering performance, for real time purposes, visualization of simulated data or Lidar data, or 3D streaming. In geovisualization, we sometimes face a kind of dichotomy between the abstraction paradigm, coming from map design and vectorial spatial data handling, and the photo-realism paradigm, coming from image processing and computer vision based on the acquisitions of 3D+T laser or images on earth. This dichotomy exists also into the various sets of knowledge and methods, coming from map design, image processing and computer vision, to represent spatio-temporal information.

Spatio-temporal Phenomena and Models. Advances in modeling and simulation of physical, social, historical of spatio-temporal phenomena and dynamics need more and more visualization support, for visuo-spatial analysis purposes. How could visualization effectively help to support perception and interpretation of data and related phenomena? Knowing that a phenomenon could be represented by raw, predicted, simulated, learned data, another complexity comes from acquisition sensors and input models, and their related imprecision to be (visually) propagated. Approaches to handle time and dynamics have been deeply investigated through years, in order to support visual analytics, visual reasoning, and change detection, based on innovative space-time cube (Andrienko and Andrienko, 2005) and leading to researches in the spatio-temporal analysis of movement, and in particular trajectories and human-based activities. 3D perspectives or simplified graphs (Hurter et al., 2009) such as generalized space-time cubes have been proposed (Bach et al., 2017) in order to explore data. In parallel, uncertainties of data (positional and semantic accuracy, logical consistency and completeness), models and phenomena remain difficult to convey and is still a major issue for geovisualization: visual variables have been explored and experimented (MacEachren, 2015; Bevis et al., 2017). Color palettes for geo-physics phenomena are still in question to improve scientific analysis and sharing (Spekat and Kreienkamp, 2007; Thyng et al., 2016), but also remain questionable. The issue of quality regarding scientific visualization, balanced with aesthetic issues is also discussed (Hanson, 2014). Spatio-temporal representations and animations are more and more used, in order to serve continuous animated visualizations of long-time data, for instance on earthquakes evolutions[1], such as remarkable data visualizations. Nevertheless, even if animations are very useful to improve the global perception of a spatio-temporal phenomenon and its general patterns, it remains difficult to detect and analyze changes, at any scales. In addition, the beautiful and so efficient graphic representation of warming stripes for climate data visualization is particularly relevant and has a strong public impact: nevertheless it is quite not adapted to complex visual analysis of climate change, regarding dynamic geographic spaces and other dynamic geophysical systems, even some parameters may be used to compare, show and extract time periods and identify some effects (Hawkins, 2018).

Visual Integration, Interaction and Immersion. Co-visualizing data, i.e. visualizing them together in a single visual display, implies difficulties caused by the potential number but also the potential heterogeneity in source, scale, content, precision, dimension and temporality. This visual integration requires to figure out graphic representation aspects to preserve legibility when combining heterogeneous data and sometimes numerous ones. Visual complexity is a major stake and innovative measures and analysis have been propose to drive better geovisualization techniques (Schnur et al., 2010; Da Silva et al., 2011; Jégou and Deblonde, 2012). Because the image processing approach here is not suitable to capture semiologic and cognitive complexities of geovisualizations, or local complexities (Touya et al., 2016). Geovisualization strengthens and revisits the *map design* process, i.e. a series of choices regarding conceptual, semantic, geometric, graphic abstractions of geospatial reality. Abstraction and schematization have been addressed by information visualization for cartography (Isenberg, 2013; Kim et al., 2013) until sketchiness techniques evaluation (Boukhelifa et al., 2012; Limberger et al., 2016). We claim here for a closer methodological approach between the 'abstraction' paradigm and the 'photo-realism' paradigm, in order to take advantages from both for the visual integration of data. Various research works propose managing continuous transitions in a same visualization, for instance between levels of abstraction, according to the distance from the image center or some rendered objects, to the scene depth, in rendering styles or through scales (Semmo et al., 2012; Trapp et al., 2015; Dumont et al., 2017). Multiplexing tools have been investigated, in order to focus on some parts of the visualization or some objects in the visualization (Pietriga et al., 2010; Pindat et al., 2012) opening a main lead for the visualization of several data types. Interaction is meant to favor exploration and perception of represented scenes, leading to immersion into virtual scenes, augmenting the real environment: numerous applications of augmented and virtual reality have been investigated for many use cases (Milgram and Kishino, 1994; Schmalstieg and Reitmayr, 2007; Normand et al., 2012). Augmented and mixed realities are opportunities, for urban design and dynamics comprehension such as non-visual perceptions, to experiment spatial perception, interaction and cognition, supporting analysis or enriching a multi-sensorial experience. These new devices require adaptation for geovisualization and visuo-spatial analysis, probably inspired by 3D geovisualization (Devaux et al., 2018), not to be only gaming-oriented or movie scenarii, but use-oriented (Jacquinod and Bonaccorsi, 2019), and targeting the *Immersive Analytics* (Chandler et al., 2015).

[1]https://volcano.si.axismaps.io/

3 MULTI-D EXPLORATION

The multidimensional characteristic of data and phenomena implies to be able to go from one representation to another, from a dimension to another, from a point of view to another, while: 1- facilitating the exploration, 2-without loosing visual landmarks and attention. We tackle the 'geovisualization issue' as a multidimensional exploration of the territory. We aim at conceiving an interactive system, allowing to design and use visualizations, based on the exploration of possible heterogeneous data and styles, through space and time, supporting to observe, analyze and interpret possible spatio-temporal phenomena on earth. This ideal system should favor some responsiveness, in order to co-design with the users, provide guidance to find the most suitable visualization for a use context, and provide ways to explore and design possible visualizations. These requirements need to orchestrate the main components of this exploration, based on the knowledge of the sets of parameters, operators and constraints. This purpose can only be fed by the identification of the main categories of problems to solve, in order to formalize and integrate them into a semi-automatic system of geovisualization, such as the following ones: 1- the capacities to respond to various uses; 2- the navigation into graphic representations through style exploration; 3- the exploration of data interaction and immersion possibilities; 4- the exploration of points of view, from the user location to their intentions. We think that they should be addressed further and deeper, with the help of a cross-disciplinary approach, from other visualization domains.

3.1 Use Exploration

As input knowledge for geovisualization, geographic approaches or direct observations help to identify the users needs, such as many user studies on preferences and task performance help to assess the efficiency and the usability (Fabrikant and Lobben, 2009; Slocum et al., 2001). Use contexts have to be investigated, in order to explicit meaningful entities and structures of geographic spaces and the phenomenon in issue (Griffin et al., 2017).

Retrieving Users Needs. To make the users express what is relevant for them, is difficult to drive on the field, and is actually done through geographic approaches, but still remains difficult to approach semi-automatically. For scientific purposes, if researchers want to visually analyze the results of a simulation, prediction or learning model, it will be relevant to identify with them what is meaningful to actually observe, according to their use context. For general public, it would be useful to better explain phenomena and their underlying uncertainties. For a flash flood, some could investigate a precise maximal extent in time related to possible submersions, affected buildings during a water flood, or various prospective scenari of rising water levels, with the help of the same geovisualization system (Fig.1). Visualization could help to show and compare realistic simulations or scenarios, interpret results from simulation, prediction or learning models, or the gap between predicted and observed data on earth, in order to refine a model; it should also support the automatic detection and identification of artifacts, patterns, breaks, changes, outliers, weak signals, in input data and initial configurations of models; but also to explore a phenomenon, in its various dimensions, spatial, temporal but also in the initial parameterization and/or measures. The exploration of the spaces of initial parameters and observations of the models, to visually compare various scenarios, and possibly to modify the computation parameterization in real time.

Improving Models of Perception and Cognition. Concerning user-centered approaches, a convergence of Geographic Information sciences with psychology and cognitive sciences (Davies et al., 2015; Martin, 2008) exists for a long time ago, in order to address what help people read and think on spaces and their related representations. Nevertheless, it remains difficult to go out visual perception issues and to model properly spatial perception and cognitive dimensions. A well conducted experimentation requires the definition of low level tasks in a simplified geographic space, in order to correctly validate the hypothesis. But in geovisualization, tasks are complex and made in a complex geographic space, not facilitating the specification of independent hypothesis, the design of controlled experimentation and the reproductibility of those experimentation. This implies to be able to retrieve rules and constraints coming from the use contexts, and to design models of perception, cognition and use for visuo-spatial reasoning.

3.2 Style Exploration

The style is simply defined as a ”set of formal and aesthetic characteristics of something” and ”a manner to practice something, defined by a set of characteristics”, in the dictionnary. Based on the definition of a pictural style, coming from linguistics and computer graphics knowledge (Willats and Durand, 2005), we reformulate the style as all what makes distinguishable and recognizable the way to design a graphic representation, based on the implicit knowledge of graphic rules and perhaps grammar rules, required to generate this representation. The style refers to a typical family of representation choices, recognizable with the help of a set of visual salient characteristics. The hypothesis to use styles is to facilitate the decoding of spatial information, by handling the repeated experience of reading one style, related to memorization and learning. When reading a graphic representation, a series of mechanisms of vision, perception and cognition is triggered, based on the visual arrangements, related to spatial arrangements in the real scene and typical from representation choices of an author, an institution, a period of time, etc. We experiment a reconciliation between computer vision and map design, with the common purpose of spatio-temporal analysis and visualization of geospatial data, while combining knowledge and

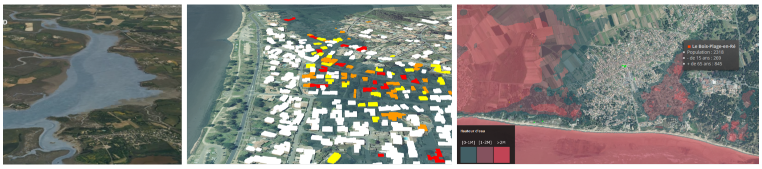

Figure 1: Flood visualizations: animated water rising in 3D (1)(Masse and Christophe, 2015); affected buildings during flash floods (2); comparison between prospective scenarii (3) experimented in iTownsResearch[2].

methods to get more a flexible approach of the geovisualization methods and tools. Combining abstract and photo-realist styles, while bringing graphic semiology (Bertin, 1967) into the 3D paradigm, and rendering capacities into (carto)graphic representations, are the main leads.

Specifying Styles for 2D, 3D, 3D+T or 3D+measure. The specification of styles could allow leveraging the levels of visual, perceptive and cognitive complexities potentially coming from the phenomenon to be represented and the related data. Capacities provided by (carto)graphic abstractions and expressive renderings methods (Barla et al., 2007) allowed us to specify several typical cartographic styles targeting expectations to have more expressiveness, visual effects, some kind of "relief" and animation, in flat surfaces and classical linear provided by GIS systems and related rendering engine: watercolorization, engraving, old map styles are specified and rendered (Christophe et al., 2016). These expressive methods are transferred to 3D, in order to provide a set of abstract styles, from a very simple to more sketchy one, in order to manipulate abstract buildings, and help the users to focus on their volume and distribution in empty spaces, and not on possible details provided by photo-realistic textured models (Cf. Fig.2). At the contrary, a very realistic 3D geovisualization, based on a high level of detail will perfectly fit to virtual and/or historical visits into the past of the city, or to represent realistically a physical phenomenon. **Hybridizing & Optimizing Styles.** Going further than transparency has led us to mix data and styles and to provide interaction tools allowing to control the level of hybridization between photo-realistic and abstract styles: we initiate a continuous transition between orthoimagery and vector data, in order to take advantages from expressivity and efficiency of both styles, based on the interpolation of graphic parameters, that could be independently controlled by the users, to design and refine the way to drive each interpolation of parameters (color palette, image textures, generated textures, abstract patterns) (Hoarau and Christophe, 2017). The design of optimization methods would offer to explore the space of possible styles of representation in geovisualization, based on the interpolation between the sets of graphic parameters of styles, and related rendering operators. From color and texture interpolation (Hoarau and Christophe, 2017) to the optimization of the space of constrained color palettes (Mellado et al., 2017), we experimented first steps. Extending existing works on style transfer (Gatys et al., 2016; He et al., 2017; Liao et al., 2017) to our complex problem would be relevant to follow.

[2]https://itownsresearch.github.io/

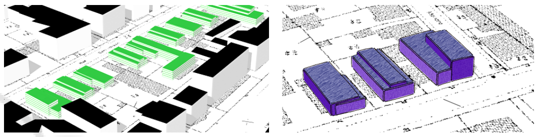

Figure 2: 3D Abstract styles(Brasebin et al., 2016).

3.3 Interaction, Immersion

Covisualization. In the context of Geographic Information Systems (GIS), the "multi-layer" paradigm prevails, but only global transparency between layers does not allow to explore data. Hybridization of data and styles required data interpolation: we propose a continuum between cartographic representation and satellite imagery, based on color and texture interpolations, in order to get more photo-realism in the abstraction, and conversely. This approach has been pursued in a interdisciplinary approach with human-computer interaction, about the design and experimentation of multiplexing cartographic tools allowing to improve co-visualization of heterogeneous data and multi-scale navigation (Lobo et al., 2017).

Augmented Perception. We face the possibility to enrich the user experience, with the help of 3D interaction and an enriched perception, not only visual, of their environment. Our purpose here is to facilitate the understanding of 3D models and related spatial structures and arrangements making the urban morphology. To visually analyze how a physical phenomenon could interact spatially with the urban morphology is at stake there, for a sea level rise or microclimatic factors, evolving into the city, in all possible dimensions. Again this issue requires to take into account what is meaningful in the characteristics of the phenomenon, but also the relevant topographic data or other data conveying meaning for vi-

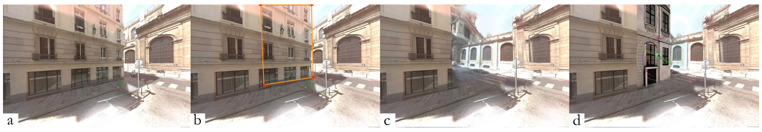

Figure 3: Urban design with augmented reality glasses: removing of and adding a building (Devaux et al., 2018).

sual analysis. In the context of urban design, we propose an extension of a classical desktop 3D geovisualization into mixed reality, in order to identify the components of the geovisualization pipeline needing to be re-adapted or extended (rendering, stylization, 3D interaction), and new components to take into account more specifically (pose estimation, occlusions, inpainting). This kind of application requires not only the integration of a high quality level of the 3D model, coming from a photogrammetric acquisition, to get the scene captured by the augmented reality device, but also to design intuitive interaction with the augmented data, whatever the resolution of the 3D model or the visualization scale. Various experimentations are made – scale modification, geometric adaptation between virtual and real scenes, style matching between added objects and existing objects in the scene – allowing the interaction et the hybridization of real and virtual. For urban design purpose, we design a use case about the implantation of a new building requiring to remove the previous one, with potential different volume, ground surface, facades textures, with the help of glasses of mixed reality (Fig.3)(Devaux et al., 2018). These approaches have to be pursued and are actually experimented in various use contexts, based on historical or climate data, to improve the visualization of urban spaces.

3.4 'Points of View'

The multidimensional exploration of the territory is finally an exploration of various points of view on the territory. This notion may cover the following aspects, but has also to be taken in a more conceptual way. It could be: 1- the location of the user or the camera, through a numeric device or not; 2- the various angles or axes, from which a phenomenon can be visualized, as elevation (street-level, oblique, ortho views, for instance), depth, time, etc.; 3- the way to conceptually and formally represent a phenomenon: a measure, a probability distribution, a scalar field, a graph, etc.; 4- the intention of the author, and the way the author may control their message to convey, i.e. an 'intentional' point of view; This proposition implies to control, orchestrate the multiple possible explorations, help the users to take benefit from modifying their point of view, according to their own use contexts, and effectively to explore data in a multidimensionnal way. This is this exploration of the diversity of possible geovisualization designs which will bring us closer to fit to the diversity of users and uses. To enrich perception until immersion, in order to be into the geographic space, more or less virtually: this issue of the experience, which could be multi-sensorial, asks to be experimented in the context of spatio-temporal phenomena related to geographic spaces.

Beyond Vision? When vision is missing or failing, we could ask rightly if 'geovisualization' still has a meaning there. We argue that the "to perceive and to understand" is still relevant and similar challenges remain to provide a mental representation of the territory. This requires a complete revisit of the needed entities meaningful for mobility, to be represented for blind people. This extension of 'geovisualization' motivate us to propose new cognitive model of geographic space representation, to support this spatial perception and real mobility tasks. Complex notions for spatial cognition, such as obstacles, empty spaces, hazardousness, uncertainty are a huge challenge for the better understanding of spatio-temporal information.

4 CONCLUSION

We claim for a cross-over between domains, in order to model how the visuo-spatial reasoning works, especially regarding complex tasks, as scientific and decision-making purposes, such as explanation and communication for final users. To be able to interface simulation, learning, or prediction models to visual analysis, will allow to facilitate and enrich the capacities of interpretation and comparison of models, simulations and scenarios, in addition to classical approaches of spatial analysis, in order to detect artifacts and changes, in space and time. We hope that visualization could facilitate the first steps of decoding, reasoning and learning. In particular, the issue of the interpretability of spatio-temporal data, from raw to simulated ones, could help to visually analyze geophysical, climatical, socio-demographic, historical phenomena and dynamics on earth. We assume that challenges are still remaining in order to reach the final goal: how geovisualization could effectively participate to visuo-spatial reasoning until the famous decision-making? In particular, uncertainty and decision-making are still investigated and experimented (Padilla et al., 2018; Kübler et al., 2019) and we hope to be able in the future to use these experiments to guide graphic representation choices for a better visualization of spatio-temporal data on earth.

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