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Methods of 3D Geovisualization of Thematic Data in the Context of Graphic Variables

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Methods of 3D Geovisualization of Thematic Data in the Context of Graphic Variables

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Abstract: This paper explores six methods for 3D geovisualization of thematic data, offering insights into how spatial information can be effectively represented in three dimensions. The main goal is to describe selected methods of 3D geovisualization of thematic data in terms of their graphic variables and thus provide an overview of how to approach these methods and their variables. The methods discussed include Point Cloud, 3D Surface, Vertical Planes, 3D Graduated Symbols, Prism Map, and Voxels. Each method is evaluated based on both 2D (e.g. color, size, shape, transparency) and 3D graphic variables (e.g. height, extrusion), which are crucial for creating clear and informative 3D geovisualizations. The study highlights the significance of color and extrusion in enhancing visualization clarity, with 3D graduated symbols standing out for their use of multiple graphic variables. The paper underscores the necessity of interactive camera controls to mitigate issues like overlap and occlusion, which can hinder data interpretation. Additionally, it addresses the challenges of perspective and realism in 3D visualizations, emphasizing the balance between visual appeal and accurate data representation. This research contributes to the field of 3D geovisualization, providing a framework for understanding and applying these methods to thematic data. The choice of a specific method always depends on the type of data and the purpose of the visualization. The findings are particularly relevant for those interested in the practical applications of 3D geovisualization.

Keywords: 3D, geovisualization, methods, thematic data, graphic variables

1. Introduction

3D geovisualization is currently on the rise and its popularity is growing, mainly due to the ability to display spatial data accurately, engagingly and interactively. However, the methods of 3D geovisualization of thematic data have not yet been clearly defined. There are many ways and methods to represent spatial data in three-dimensional form. Some methods are more suitable for topographic and elevation data, while others are more suitable for thematic data. The advantages and disadvantages of 3D geovisualization were discussed by Shepherd (2008). He considers the advantages to be, for example, additional display space, the possibility of displaying more variables, or solving the problem of overlapping symbols. On the other hand, he lists the disadvantages as, for example, variable scale across 3D scenes, distortion of the view, or problems with transparency and cast shadows. It is necessary to note that not all 3D is realistic, nor all realistic visualizations are 3D. On the other hand, level of realism can be studied with immersivenes, showing that not all realistic representations are immersive (Çöltekin et al., 2016). When creating 3D geovisualizations, it is necessary to pay attention to the graphic variables of individual visualization methods, similar to classic 2D cartography.

Graphic variables were originally defined by Bertin (1967) and must be considered when creating geovisualizations. One of the most important graphic variables across different methods is color. The effective use of color in the visualization of meteorological data was addressed by (Stauffer et al., 2015). Vuckovic et al. (2021) claims that nowadays there is an increasing need for combining both 2D and 3D visualizations and their inherent navigation and exploration techniques. A specific area of 3D geovisualization is the representation of meteorological data in an urban context. Co-visualizing simulated climate data with morphological urban data would allow supporting the validation of climate simulation models, by comparing simulation results with morphological indicators used as simulation input data, such as a suitable visual analysis of relationships between urban heat islands and the urban environment (Gautier et al., 2020a). 3D geovisualizations can be applied in a wide range of fields, such as infographics (Konicek et al., 2024) or tactile cartography (Voženílek and Vondrakova, 2015).

2. Graphic Variables

Graphic or visual variables describe the graphic dimensions in which a map or other visualization can be changed to encode information. Graphic variables are differences in map elements perceived by the human eye. Regardless of the type of map, these are basic ways of distinguishing graphic symbols (Axis Maps, 2023). For example, Garlandini and Fabrikant (2009) dealt with the evaluation of the effectiveness and efficiency of visual variables for the visualization of geographic information. Visual variables were originally described by the French cartographer Jacques Bertin (1918–2010) in the book Sémiologie Graphique (Semiology of Graphics) in the original 1967 edition, revised in 1983 (Roth, 2017). The original so-called "retinal variables" (Bertin, 1967) included:

- position;
- size;
- shape;
- color value;
- color hue;
- orientation;
- texture/pattern.

This list was then gradually expanded by other cartographers (MacEachren, 2004; Morrison, 1974; Roth, 2017):

- color saturation;
- arrangement;
- crispness/fuzziness;
- resolution;
- transparency.

In addition, the 3D environment allows the evaluation of other graphic variables, such as perspective, camera, lighting, shading, atmospheric effects (Krejčí, 2018), height, extrusion, object surface (pattern, shading), light emission (Limberger et al., 2023) or fog (Vetter, 2023). For the purposes of this paper, four 3D graphic variables were selected to evaluate 3D geovisualization methods, namely:

- height (vertical dimension of the symbol);
- extrusion (expansion of a 2D object into the third dimension);
- camera (the place from which the user looks at the object or scene);
- perspective (the way an object or scene is rendered to appear realistic in terms of depth and space).

The 2D and 3D graphical variables that were evaluated for methods of 3D geovisualization of thematic data are graphically depicted in Figure 1.

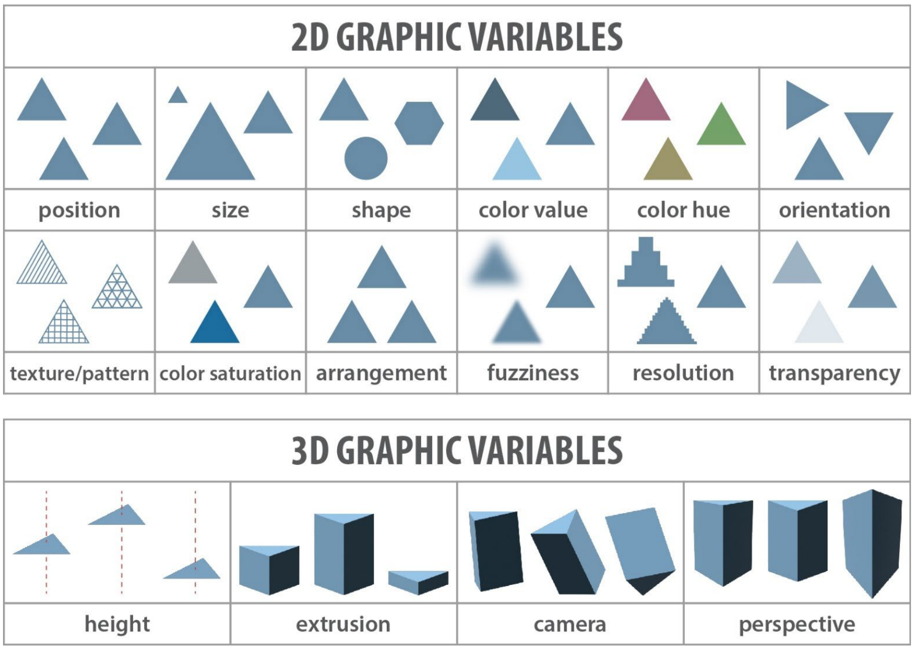

Figure 1. Graphic variables selected for evaluation of methods of 3D geovisualization of thematic data.

3. Methods of 3D Geovisualization of Thematic Data

For the purposes of this paper, the six most used methods of 3D geovisualization of thematic data were selected based on a literature review – Point Cloud, 3D Surface, Vertical Planes, 3D Graduated Symbols, Prism Map and Voxels. The selected methods are graphically illustrated in simplified form in Figure 2. These methods have different characteristics, and the choice of method should be made according to the type of data and the purpose of the visualization. For example, Prism Map and Voxels are very similar, but one is based on different sized area units (e.g. administrative) and the other is created from a regular square grid. On the other hand, 3D Surface is suitable for continuous phenomena (e.g. air temperature) and Vertical Planes are suitable for line data with thematic information (e.g. road network). For Point Cloud and 3D Graduated Symbols, the symbols can be distributed regularly or irregularly. The Horizontal Planes method was described and evaluated by Žejdlík and Voženílek (2024) and is therefore not included in this article.

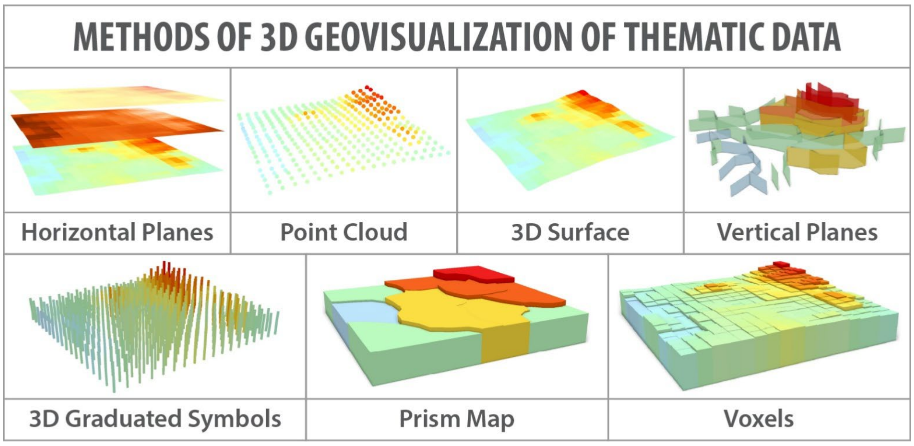

Figure 2. Graphic representation of seven selected methods of 3D geovisualization of thematic data.

3.1. Point Cloud

A point cloud is a type of discrete visualization where each point is represented by three coordinates. It can be a 2D point cloud, where all points have a constant Z coordinate, or a 3D point cloud, where the Z coordinate is variable. Point clouds can be distributed randomly or in a regular grid (Figure 3). Ideally, the user can dynamically change the size and density of the dots to achieve the best possible visual analysis (Gautier et al., 2020b).

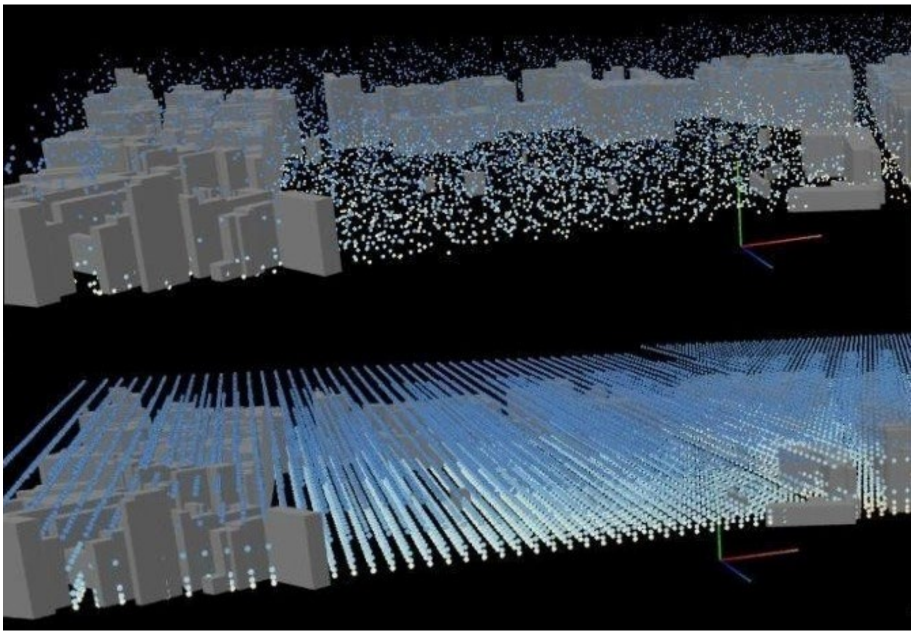

Figure 3. Example of the Point Cloud method – air temperature (source: Christophe et al., 2022).

- Position: The position of all points in the point cloud is predefined, and the points can be distributed regularly or irregularly.
- Size: The size of the points needs to be set appropriately with respect to the scale, as too large points could cause significant overlap, and too small points would make it difficult to determine, for example, the color of the point.
- Shape: The points in the point cloud are always spherical.
- Color: Color plays a significant role in the case of a point cloud, as the points can be colored based on the selected attribute, which can significantly improve user interpretation. In combination with, for example, height, both variables can represent either the same attribute or different attributes, thus representing multiple variables within one visualization.
- Texture/pattern: It is possible to apply a texture or pattern to the points, but it is preferable to use only color, as the texture or pattern is very difficult to distinguish in the case of small points.
- Arrangement: Points can be arranged either regularly (in a regular grid with a constant distance between points) or irregularly (for example, randomly).
- Uncertainty: In the case of a point cloud, the uncertainty can be represented using other graphic variables, e.g. transparency (the greater the transparency, the greater the uncertainty) or size (the smaller the point, the greater the uncertainty).
- Transparency: Transparency can be applied to the points, which can partially resolve the overlap of the points, but may then result in color blending and poorer interpretation.
- Height: All points can be placed at the same height, or the height can be variable based on the selected attribute. Multiple point clouds can also be displayed on top of each other.
- Camera: For quality interpretation, it is necessary to provide interactive camera control to explore all parts of the point cloud, as points can often overlap.
- Perspective: The point cloud can be rendered in a plane or with the curvature of the Earth considered, depending on the scale and purpose of the visualization.

For the Point Cloud method, three graphic variables are not applied: orientation (points have the same orientation in all cases), resolution (it is a visualization from vector data) and extrusion (the size of the point is defined by its diameter, not by extrusion).

3.2. 3D Surface

A 3D surface is a method of continuous visualization usually created by interpolating points from a point cloud. The pixel height (Z coordinate) is variable depending on the value of the phenomenon. 3D surfaces are most often used to represent elevation (digital elevation models), but they can also be used, for example, to represent socio-economic phenomena (so-called social or digital surfaces – Figure 4). Socioeconomic data have different characteristics than data from physical geography. Therefore, it is not enough to use the same methods and just change the data. It is always necessary to know the investigated phenomenon and adapt the visualization method to it (Jakobi and Nemes Nagy, 2006).

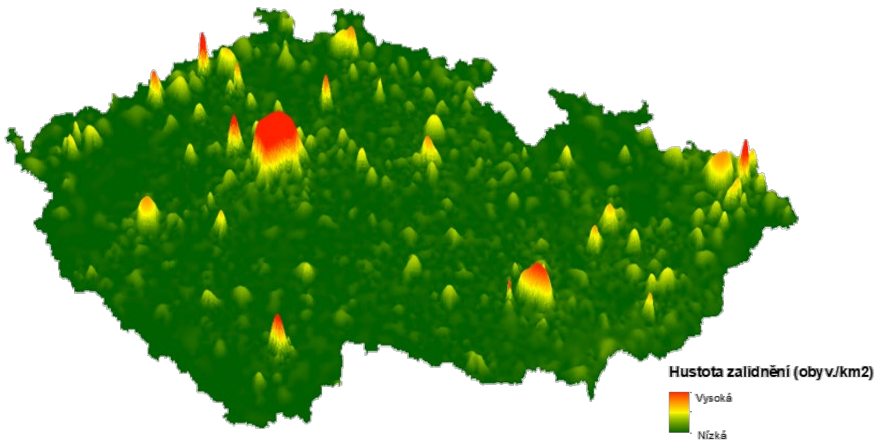

Figure 4. Example of the 3D Surface method – population density of Czechia (source: Stískalová, 2017).

- Color: The color of the individual cells of the 3D surface is very important, as it allows the user to read the exact, or at least approximate, values of the cells. By using only one color for the entire surface, the user would have to rely only on estimating the values based on the height of the cells.
- Arrangement: When displaying multiple surfaces within a single visualization, the surfaces should be logically arranged according to the selected attributes. In the case of a 3D surface, however, it is recommended that only one surface is used within one visualization.
- Uncertainty: Uncertainty can be represented, for example, by color brightness or transparency (eg, the higher the transparency, the higher the uncertainty).
- Resolution: Resolution (pixel size) affects the graininess of the resulting image – high resolution means more detailed and smoother visualization, but a larger volume of data.
- Transparency: Transparency enables partial visibility of the topographic background (e.g. state borders, cities). However, if set incorrectly, transparency can distort the visualization due to the intermingling of the colors of the thematic layer and the background.
- Height: For a 3D surface, the cell height (Z coordinate) is variable based on a value (for example, temperature – the higher the temperature, the higher the cell is within the visualization).
- Camera: For quality interpretation, it is necessary to ensure interactive control of the camera to explore all parts of the 3D surface, as some parts of the surface may overlap others.

- Perspective: The 3D surface can be rendered without or with the curvature of the Earth considered, depending on the scale and purpose of the visualization.

For the 3D Surface method, six graphics variables are not applied. Four of them are defined by the nature of the source data, and therefore cannot be modified in any way. These are: position (location of the 3D surface in space), size (spatial extent of the data), shape (depending on the source data – the 3D surface can be based on a rectangular grid or a grid that is, for example, clipped according to state borders) and orientation (defined by the orientation of the source raster). The other two variables that don't apply to 3D surfaces are texture/pattern (texture or pattern can't be applied to pixels) and extrusion (for a 3D surface, the third dimension is represented by pixel height, not extrusion).

3.3. Vertical Planes

Vertical planes are usually located in the middle of urban roads and rendered by extruding vertically the linear geometry of the road network (Figure 5). In order to answer possible occlusion issues, transparency can be applied to the vertical planes (Gautier et al., 2020a). Jedlička et al. (2024) refer to the method as 3D Flow Map, which is based on Flow Map – a method of thematic cartography used for the expression of linear phenomenon with quantitative or qualitative attributes alongside the geometry of the line.

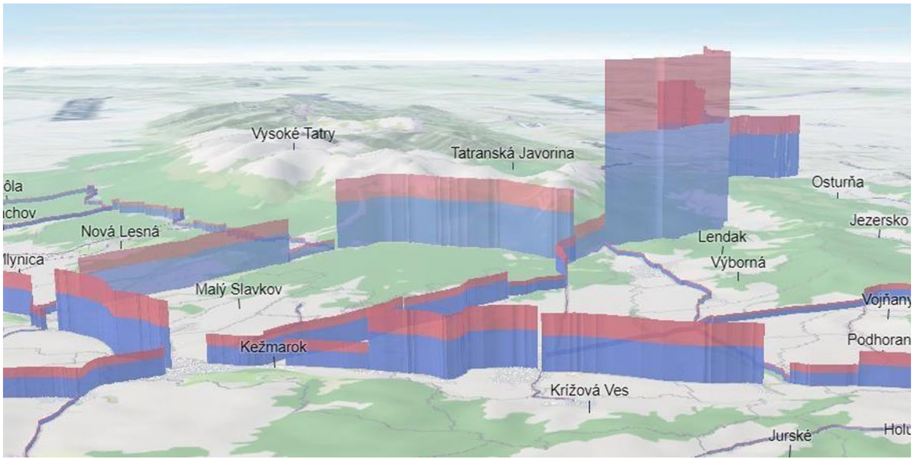

Figure 5. Example of the Vertical Planes method – the color of the line determines the vehicle category, the height of the line corresponds to the number of vehicles (source: Jedlička et al., 2024).

- Color: Vertical planes can be colored qualitatively (for example, according to the type of road, where the quantity is represented, for example, by extrusion) or quantitatively (where the intensity of the color corresponds to the value of the given phenomenon). Color and extrusion can represent the same or different attributes.
- Texture/pattern: The use of texture or pattern on vertical planes can enrich the visualization with additional qualitative or quantitative information. But more significant variables such as color or extrusion should be used as a priority.

- Uncertainty: In the case of vertical planes, uncertainty can be represented using other graphic variables, e.g. transparency (the higher the transparency, the higher the uncertainty) or extrusion (the lower the plane, the higher the uncertainty).
- Transparency: Transparency can be applied to planes, which can partially resolve their overlap, but can result in color blending and poorer interpretation.
  Height: Vertical planes should be placed on the ground, as they often come from e.g. the road network or contour lines. In the case of displaying multiple planes above each other, the planes can connect to each other or have a gap between them.
- Extrusion: Extrusion determines the vertical dimension of the plane, which can be variable based on the feature value. Extrusion can also be constant for all planes while changing other variables (such as color).
- Camera: Vertical planes may overlap, so it is important to provide interactive camera control.
- Perspective: Vertical planes can be rendered without or with the curvature of the Earth considered, depending on the scale and purpose of the visualization.

For the Vertical Planes method, six graphic variables are not applied: position (defined by source line data – e.g. road networks, contours), size (line length, with the vertical dimension determined by extrusion), shape (always a line), orientation (defined by line orientation), arrangement (defined by source line data) and resolution (it is visualization from vector data).

3.4. 3D Graduated Symbols

This method is based on 2D graduated symbols method used in thematic maps. Symbols can take many forms, from 3D bars (Figure 6) to spheres to pie charts, while the size of these elements depends on the value (eg column height, sphere diameter). Testing suitable representations of quantitative spatial data in 3D virtual environments using 3D graduated symbols was dealt with by Bleisch (2011). Six potentially appropriate proportional symbols for the display of quantitative data in virtual environments were experimentally tested: 2D bars, 3D bars, and 2D circles, with and without reference frames indicating the largest possible value (Bleisch, 2011). Stoter et al. (2008) used 3D graduated symbols to visualize the noise level using so-called virtual microphones. A virtual microphone, specified with x, y, z coordinates, is a point that reports what the noise level would be at a certain location under given circumstances.

Figure 6. Example of the 3D Graduated Symbols method – distribution of cigar makers in the East End of London in 1881 and 1887 (source: Shepherd, 2008).

- Position: 3D graduated symbols can be placed regularly (in a regular grid) or irregularly (for example, one symbol for one country).
- Size: The size of 3D graduated symbols is a very important variable, as it represents the values of elements (e.g. column height, circle diameter). Higher values should therefore be represented by higher columns, etc.
- Shape: 3D symbols can be of different shapes, being 2D (eg circles, columns) or 3D objects (eg spheres, cubes, cylinders, pyramids). According to the shape, 3D graduated symbols can be divided into point (e.g. circles, spheres), column (e.g. columns, cylinders) and other (e.g. structural, pie chart). A specific case of a 3D graduated symbol can be e.g. meteogram or age pyramid.
- Color: Like other methods, color also plays an important role in the case of 3D graduated symbols. The color of the symbols in combination with their size (diameter, height, extrusion, etc.) increases user friendliness and the ability of correct interpretation.
- Orientation: The orientation depends on the symbol type. For example, with a spherical symbol, orientation does not apply because the spheres always have the same orientation, but when using a cube as a symbol, orientation can be significant.
- Texture/pattern: The use of texture and pattern depends on the type of symbol. For small symbols, the texture/pattern might be hard to read. In general, however, the use of texture/pattern can enrich the visualization with additional qualitative or quantitative information.
- Arrangement: 3D symbols can be arranged regularly or irregularly.

- Uncertainty: Uncertainty can be represented, for example, using transparency (the greater the transparency, the higher the uncertainty) or texture/pattern.
- Transparency: Transparency can be applied to symbols, which can partially resolve their overlap, but may result in color blending and poorer interpretation.
- Height: Symbols can either be placed at a specific height above the ground and resized (e.g. sphere diameter) or they can be placed on the ground and the values are shown at different heights (e.g. bar height).
- Extrusion: Extrusion is applied to bar symbols, where the size of the extrusion (height) represents the element values.
- Camera: Symbols can overlap, so it is important to provide interactive camera control.
- Perspective: 3D graduated symbols can be rendered without or with the curvature of the Earth considered, depending on the scale and purpose of the visualization.

For the 3D Graduated Symbols method, the graphic variable resolution is not applied, since it is a visualization from vector data.

3.5. Prism Map

A prism map is a 3D choropleth map with extruded height to encode a numerical attribute (Figure 7). Prism maps are predominantly used for visual impact, and the unfamiliarity with prism maps hampers their understanding (Field, 2018). Height (the visual variable used by prism maps) is far more accurate for interpreting associated quantitative values than brightness (the visual variable commonly used by choropleth maps), but perspective foreshortening and oblique viewing angles can result in distortion and excessive occlusion in prism maps (Cleveland and McGill, 1984).

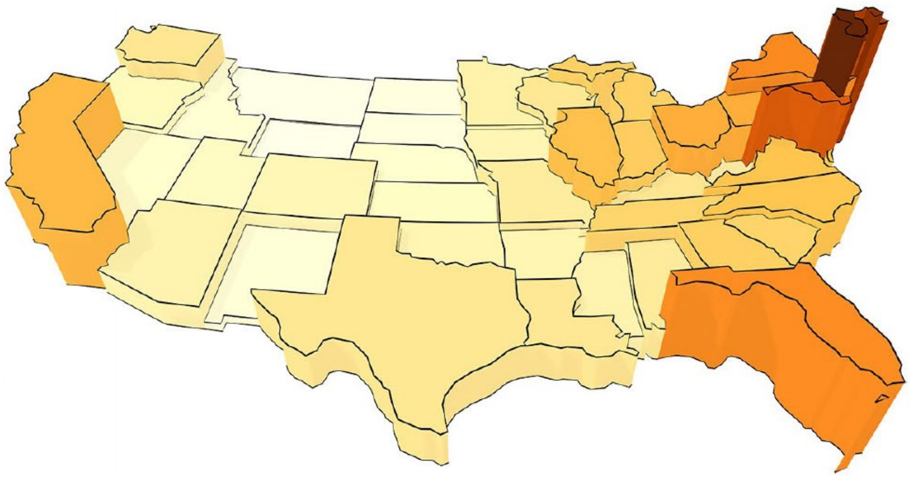

Figure 7. Example of the Prism Map method – population density in US states (source: Yang et al., 2020).

- Color: Like other methods, color plays an important role in the case of prism map. It can be combined with other variables (especially texture/pattern and extrusion), whereby these variables can express the same attribute, or different attributes can be represented by e.g. color and height.
- Texture/pattern: Texture and pattern can enrich the visualization with additional qualitative or quantitative information. But more significant variables such as color or extrusion should be used as a priority.
- Uncertainty: In the case of a prism map, uncertainty can be represented by, for example, transparency (the higher the transparency, the higher the uncertainty), color or texture/pattern.
- Transparency: The use of transparency in the case of a prism map is rather inappropriate, as the individual administrative units usually follow each other, and the transparency could worsen the interpretation of the used colors and extrusions.
- Height: The prism map should be placed on the ground, as it is usually based on, for example, administrative units. However, placing the prism map at a certain height can allow visibility of the topographic background.
- Extrusion: The extrusion determines the vertical dimension of the administrative units, with the size of the extrusion (height) representing the element values.
- Camera: In the case of the prism map, there is not as much overlap as with other methods. Nevertheless, it is advisable to enable interactive control of the camera.
- Perspective: A prism map can be rendered without or with the curvature of the Earth considered, depending on the scale and purpose of the visualization.

For the Prism Map method, six graphic variables are not applied: position, size, shape, orientation, arrangement (given by the source data of administrative units – e.g. countries, regions) and resolution (it is a visualization from vector data).

3.6. Voxels

In geovisualization using voxels, the data is represented by blocks with different heights depending on their values (Figure 8). It has common elements with a 3D graduated symbols and prism map. Unlike 3D graduated symbols, in the case of voxels, adjacent blocks (voxels) are connected to each other, and unlike a prism map, all polygons have the same size. Rae (2016) used The Global Human Settlement Layer data to represent population in selected cities using voxels. His approach was applied in 2018 by The Pudding to create an interactive web map application, using the same dataset to represent population for the entire world (The Pudding, 2024).

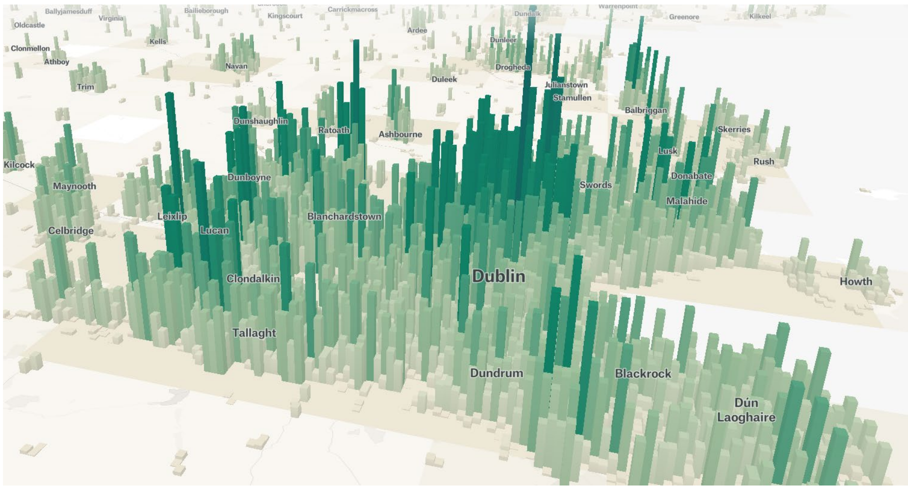

Figure 8. Example of the Voxels method – population density in Dublin (source: The Pudding, 2024).

- Size: Size is equivalent to resolution in the case of voxels, as voxel size affects the detail of the resulting visualization.
- Color: Color plays an important role in the case of voxels, and it is advisable to combine color especially with extrusion. Both variables can represent the same attribute, or different attributes can be represented by color and extrusion.
- Texture/pattern: Texture and pattern can enrich the visualization with additional qualitative or quantitative information. However, if the voxel size is small, the texture or pattern may be difficult to distinguish.
- Uncertainty: For voxels, uncertainty can be represented by, for example, transparency (the higher the transparency, the higher the uncertainty), color, or texture/pattern.
- Transparency: The use of transparency in the case of voxels is inappropriate, as individual voxels usually connect to each other, and transparency could worsen the interpretation of the used colors and extrusions.
- Height: Like prism map, voxels should be placed on the ground. However, the placement of voxels at a certain height can allow visibility of the topographic background.
- Extrusion: The extrusion determines the vertical dimension of the voxels, with the size of the extrusion (height) representing the feature values.
- Camera: In the case of voxels, there is not as much overlap as with other methods. Nevertheless, it is advisable to enable interactive control of the camera.
- Perspective: Voxels can be rendered without or with the curvature of the Earth considered, depending on the scale and purpose of the visualization.

For the Voxels method, five graphic variables are not applied: position, orientation (defined by the source square grid), shape (always a block), arrangement (voxels are always based on a regular square grid), and resolution (it is a visualization from vector data).

4. Conclusions

The paper provides an overview of six selected methods of 3D geovisualization of thematic data – Point Cloud, 3D Surface, Vertical Planes, 3D Graduated Symbols, Prism Map and Voxels. These methods were described in the context of graphic variables. All 16 graphic variables occur in neither of the six methods. The most variables (15) are applied to the 3D graduated symbols method. The most important graphic variables across all methods are color hue, saturation and value, which can be edited for all methods. Color makes visualizations user-friendly and easy to interpret. Another very important variable is extrusion, which does not only apply to point clouds and 3D surfaces. Height is significant for three methods (point cloud, 3D surface and 3D graduated symbols). The orientation can only be changed for 3D map diagrams. The resolution can only be changed for 3D surfaces, as it is a visualization from raster data.

The combination of multiple variables (e.g. color and height, color and extrusion) can help in the correct interpretation if the same attribute is represented (e.g. voxels – the air temperature is represented both by the extrusion of the voxel and its color) or enable a complex visualization if different attributes are represented (e.g. vertical planes – air temperature is represented by the color of the plane, relative humidity is represented by the extrusion of the plane). Correctly setting graphic variables is essential for the effectiveness of a given visualization so that the information is correctly interpreted by the user. If the user is an expert in a given field, the ideal solution is to provide an interactive visualization environment where it is possible to dynamically change data and visualization methods based on their own preferences and experience.

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The authors report there are no competing interests to declare.

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References:

Axis Maps. (2023). Visual Variables. Cartography Guide - A Short, Friendly Guide to Basic Principles of Map Design. https://www.axismaps.com//guide/visual-variables

Bertin, J. (1967). Sémiologie graphique: Les diagrammes, les réseaux, les cartes. Gauthier-Villars.

Bleisch, S. (2011). Toward Appropriate Representations of Quantitative Data in Virtual Environments. Cartographica, 46, 252–261. https://doi.org/10.3138/carto.46.4.252

Christophe, S., Gautier, J., Chapron, P., Riley, L., & Masson, V. (2022). 3D geovisualization for visual analysis of urban climate. Cybergeo. https://doi.org/10.4000/cybergeo.38518

Cleveland, W. S., & McGill, R. (1984). Graphical Perception: Theory, Experimentation, and Application to the Development of Graphical Methods. Journal of the American Statistical Association, 79(387), 531–554. https://doi.org/10.1080/01621459.1984.10478080

Çöltekin, A., Lokka, I., & Zahner, M. (2016). ON THE USABILITY AND USEFULNESS OF 3D (GEO)VISUALIZATIONS – A FOCUS ON VIRTUAL REALITY ENVIRONMENTS. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLI-B2, 387–392. https://doi.org/10.5194/isprsarchives-XLI-B2-387-2016

Field, K. (2018). Cartography. (1st ed.). Esri Press.

Garlandini, S., & Fabrikant, S. I. (2009). Evaluating the Effectiveness and Efficiency of Visual Variables for Geographic Information Visualization. In K. S. Hornsby, C. Claramunt, M. Denis, & G. Ligozat (Eds.), Spatial Information Theory (pp. 195–211). Springer. https://doi.org/10.1007/978-3-642-03832-7_12

Gautier, J., Brédif, M., & Christophe, S. (2020). Co-Visualization of Air Temperature and Urban Data for Visual Exploration. https://doi.org/10.1109/VIS47514.2020.00021

Gautier, J., Christophe, S., & Brédif, M. (2020). Visualizing 3D climate data in urban 3D models. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLIII-B4-2020. https://doi.org/10.5194/isprs-archives-XLIII-B4-2020-781-2020

Jakobi, Á., & Nemes Nagy, J. (2006). Digital surface in social geography. Az Eötvös Loránd Tudományegyetem Térképtudományi És Geoinformatikai Tanszékének Évkönyve, 193–200.

Jedlička, K., Andrš, T., Čerba, O., Mildorf, T., Beran, D., Hájek, P., & Kepka, M. (2024). INTERACTIVE CARTOGRAPHY OF AIR QUALITY: A METHOD FOR TRAFFIC POLLUTION ANALYSIS. Proceedings, 9th International Conference on Cartography and GIS, 16-21 June 2024, Nessebar, Bulgaria, 373–385.

Konicek, J., Voženílek, V., Barvíř, R., & Vondráková, A. (2024). Quantitative Approach for Assessing Infographics in Atlas Cartography. Geographia Cassoviensis. https://doi.org/10.33542/GC2024-1-03

Krejčí, M. (2018). Dynamické grafické proměnné ve 3D mapách [Diploma thesis, Masaryk University]. https://theses.cz/id/35lr4j/

Limberger, D., Scheibel, W., Döllner, J., & Trapp, M. (2023). Visual variables and configuration of software maps. Journal of Visualization, 26(1), 249–274. https://doi.org/10.1007/s12650-022-00868-1

MacEachren, A. M. (2004). How Maps Work: Representation, Visualization, and Design (1st edition). The Guilford Press.

Morrison, J. L. (1974). A theoretical framework for cartographic generalization with the emphasis on the process of symbolization. International Yearbook of Cartography, 14(1974), 115–127.

Rae, A. (2016). The Global Human Settlement Layer: An amazing new global population dataset. http://www.statsmapsnpix.com/2016/10/the-global-human-settlement-layer.html

Roth, R. E. (2017). Visual Variables. In International Encyclopedia of Geography (pp. 1–11). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118786352.wbieg0761

Shepherd, I. D. H. (2008). Travails in the Third Dimension: A Critical Evaluation of Three-Dimensional Geographical Visualization. In Geographic Visualization (pp. 199–222). John Wiley & Sons, Ltd. https://doi.org/10.1002/9780470987643.ch10

Stauffer, R., Mayr, G. J., Dabernig, M., & Zeileis, A. (2015). Somewhere Over the Rainbow: How to Make Effective Use of Colors in Meteorological Visualizations. https://doi.org/10.1175/BAMS-D-13-00155.1

Stískalová, P. (2017). COMPARISON OF SOCIAL SURFACES FOR STUDYING OF DEMOGRAPHIC PHENOMENON [Bachelor thesis, Department of Geoinformatics, Faculty of Science, Palacký University Olomouc]. https://www.geoinformatics.upol.cz/dprace/bakalarske/stiskalova17/index.html

Stoter, J., de Kluijver, H., & Kurakula, V. (2008). 3D noise mapping in urban areas. International Journal of Geographical Information Science, 22(8), 907–924. https://doi.org/10.1080/13658810701739039

The Pudding. (2024). Human Terrain. https://pudding.cool/2018/10/city_3d

Vetter, M. (2023). The usage of “fog” as a visual variable in 3D-cartographic virtual reality environments. Abstracts of the ICA, 6, 1–2. https://doi.org/10.5194/ica-abs-6-263-2023

Voženílek, V., & Vondrakova, A. (2015). TACTILE MAPS BASED ON 3D PRINTING TECHNOLOGY. SOCIETY, INTEGRATION, EDUCATION. Proceedings of the International Scientific Conference, 3, 193. https://doi.org/10.17770/sie2014vol3.732

Yang, Y., Dwyer, T., Marriott, K., Jenny, B., & Goodwin, S. (2020). Tilt Map: Interactive Transitions Between Choropleth Map, Prism Map and Bar Chart in Immersive Environments. https://doi.org/10.48550/arXiv.2006.14120

Žejdlík, J., & Voženílek, V. (2024). Evaluation of 3D geovisualization of volumetric geospatial data in the form of horizontal planes using selected software. Geographia Cassoviensis. https://doi.org/10.33542/GC2024-1-01