2D and 3D Presentation of Spatial Data: A Systematic Review

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ABSTRACT

The question whether to use 2D or 3D for data visualization is generally difficult to decide. Two-dimensional and three-dimensional visualization techniques exhibit different advantages and disadvantages related to various perceptual and technical aspects such as occlusion, clutter, distortion, or scalability. To facilitate problem understanding and comparison of existing visualization techniques with regard to these aspects, this report introduces a systematization based on presentation characteristics. It enables a categorization with respect to combinations of static 2D and 3D presentations of attributes and their spatial reference. Further, it complements existing systematizations of data in an effort to formalize a common terminology and theoretical framework for this problem domain. We demonstrate our approach by reviewing different visualization techniques of spatial data according to the presented systematization.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Graphical user interfaces (GUI) H.5.2 [Information Interfaces and Presentation]: User Interfaces—Theory and methods

1 INTRODUCTION

Visualization, as a form of visual communication, can be described as the process of transforming (non-visual) data into artifacts accessible to the human mind. Its major purpose is the effective communication of data, with a strong focus on – but not limited to – visual terms and artifacts. State-of-the-art technology enables the generation of such image artifacts in real-time using 3D graphics. Especially, the increasing computing power and advances in rendering hardware during the last three decades laid the foundations of today's interactive visualizations of large-scale data sets. With these increasing capabilities, the question, whether to use 2D or 3D data presentations, is recurrently raised. Visualization designers and engineers are nowadays confronted with a number of choices for the design, implementation, and integration of visualization techniques.

Motivation. While various systematizations of the data space exist [34], there are only few differentiations with respect to the presentation itself, such as photorealistic and non-photorealistic rendering (PR and NPR) [67], static or dynamic presentations [6], or the dimension (2D or 3D). However, a presentation-oriented systematization is of particular interest because the effectiveness of communication and thus, human problem solving and decision making performance varies enormously (100:1) with different presentations [29]. Specifically, the suitability of a presentation influences the speed at which solutions are developed, the number of errors made, as well as the comprehension and visual working memory capacity [45] during this process. According to [29], a fundamental break misconception can be pointed out: *more is better*. Hence, investigations are required, on how these presentation characteristics and influences interact.

Today, it is assumed that approximately 60-80% of the data available can be interpreted as spatial data or geodata [28]. Thus, it is an important category with a strong relevance in visualization and represents an ideal starting point for such investigations.

Problem Statement. Related research indicates that the choice whether to use 2D or 3D for data visualization depends on various factors such as data complexity, display technology, the task, or application context. One example refers to the relation of available screen-space and the number of items to display. In [61], a case study focusing on the application of 2D and 3D presentations for the visualization of object-oriented systems is presented. Here, the perception of a given presentation is evaluated using the ratio of the number of objects perceived and the total number of objects o. For a given display resolution (400^2 pixels), their research indicates the existence of a boundary value at which 3D presentations exhibit higher context perception ($o > 250$) than 2D presentations ($o < 250$). Further, researching the effects of 2D and 3D on spatial memory shows no significant differences [15, 14]. Tory et al. conducted a number of experiments of 2D, 3D, and combined visualizations for estimation tasks of relative positioning and orientation as well as region selection [58]. Their results show that 3D can be effective for approximate navigation and relative positioning, but 2D is more suitable for precise measurement and interpretation. In general, *combining* 2D and 3D achieves a good to superior performance and increases confidence during problem solving.

These examples support the thesis that the question whether to use 2D or 3D for data visualization is difficult to decide. Especially, the respective advantages and disadvantages of 2D and 3D presentations, such as occlusion, clutter, distortion, or scalability, have to be considered for an effective visualization design.

Contributions. To facilitate the decision process, common criteria that reflect the characteristics of the individual need to be established visualization techniques. While previous work focused on the categorization into 2D or 3D techniques only, this work introduces a more detailed systematization by distinguishing presentations of *attribute space* and *reference space* according to their dimensionality. This allows for a better comparison of existing visualization techniques. To summarize, this report makes the following contributions:

1. We introduce a novel systematization of visualization techniques for spatial data with respect to static 2D or 3D presentation of their attribute and reference space displayed on a 2D output medium.

2. We categorize and discuss exiting visualization techniques according to this systematization.

3. We present future trends and research steps towards the development of guidelines for 2D and 3D visualization designs.

This paper is structured as follows. Section 2 presents and describes the systematization as the major contribution of this paper. Section 3 categorizes and discusses existing visualization techniques with respect to the systematization. Subsequently, Section 4 presents enhancements and describes future research directions. Finally, Section 5 concludes this report.

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2 Systematization

This section proposes a novel systematization that distinguishes between dimensionality of the presentation of the data values and the presentation of the reference space. First, we introduce termini and definitions for the data and presentation space (Sec. 2.1) and afterwards present the systematization (Sec. 2.2).

2.1 Termini and Definitions

Today's definitions in the field of information visualization vary considerably in literature. Even simple terms, such as "attribute" or "data space" are defined differently [66]. To avoid possible ambiguities, we give a brief description of our understanding of relevant notions.

The process of visualization operates on the level of data and on the level of presentation. Extending the visualization reference model of Card [12], Chi [13] introduced the concept of the data reference model, which is widely accepted in literature [2, 17, 40]. Based on a schematic data flow, this model distinguishes between operations within *data space* and within *presentation space*.

Data space. The base of every visualization are data. Since data can differ with respect to a number of properties (e.g., structure, dimension, or source), various categorizations have been established. Recently, Kehrer and Hauser [34] categorized spatio-temporal, multivariate, multi-modal, multi-run, and multi-model scientific data. The first property refers to the spatio-temporal context of the observed data and the second to the dimensionality. The remaining three refer to specific data sources. They conclude that these properties characterize the principle structure of the data, which is crucial to visualization.

For spatial data, a *spatial reference* is always present. Within it, observation points are defined, where the observed data values are given. The task-oriented relationship between them are summarized by Andrienko and Andrienko [4] in two questions: *"What are the characteristics corresponding to the given reference?"* and *"What is the reference corresponding to the given characteristics?"*. According to Keller and Keller [35] this involves a differentiation between *independent* variables v (location of an observation point, i.e., spatial coordinates) and *dependent* variables d (observed data values, e.g., temperature or speed). The independent variables define an n-dimensional *reference space*, while the dependent variables define an m-dimensional *attribute space*. For spatial data, the reference space is typically 2D or 3D ($n \in \{2,3\}$), whereas the attribute space can be multi-dimensional ($m \in \mathbb{N}$).

Presentation space. The presentation space has been analyzed by Bertin [8]. He introduces the concept of visual variables. However, there are only a few categorizations according to certain aspects, such as the appearance (non-photorealistic rendering or photorealistic rendering) [67], the representation data type of the visualization artifacts (raster or vector graphics) [46], the handling of time using static (stills) or dynamic (animation) approaches [6], as well as the dimension of the presentation (2D or 3D).

In this paper we focus on the dimensional aspect. The presentation space is constructed from *graphical elements*, which consist of visual variables (e.g., size, shape, color, and texture). Two-dimensional presentations are assembled only from 2D graphical elements, such as points, lines, and polygons. On the other hand, three-dimensional presentations utilize 3D graphical elements, such as solids or free-form-surfaces.

Given our previous discussion on the data space, a global distinction of 2D and 3D is no longer sufficient. We rather have to distinguish between the *presentation of* the attribute space $\mathcal{A}$ and the *presentation of* the reference space $\mathcal{R}$. The following section will introduce the reader to such a systematization by giving a formal definition and afterwards explaining the categorization with examples of existing visual techniques.

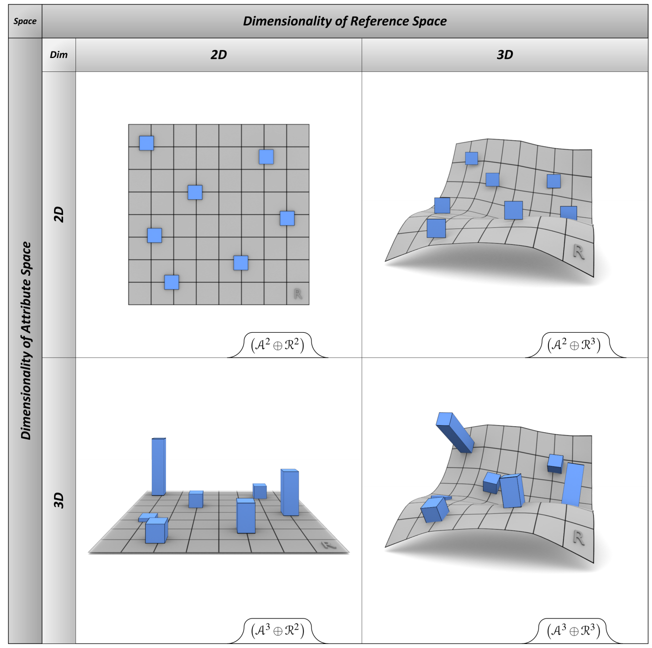


Figure 1: Systematization of visualization techniques based on the dimensionality of the attribute space's and reference space's presentation ($\mathcal{A}$ and $\mathcal{R}$ respectively). For simplicity and clarity, the visual variables of the attribute representations are limited to a single color (blue) and a single item shape (square).

2.2 Categorization of 2D and 3D Techniques

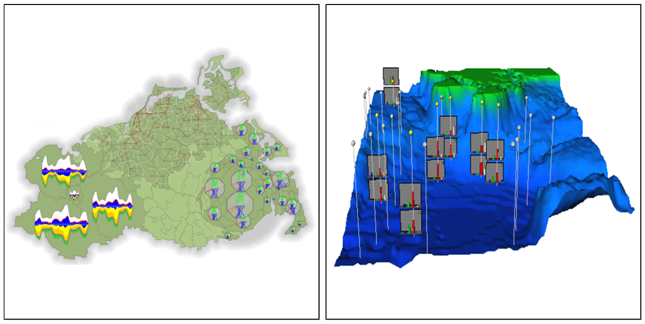
We propose a systematization with respect to combinations of 2D and 3D presentations of the attribute space ($\mathcal{A}$) and the reference space ($\mathcal{R}$). For this purpose we introduce a notation to index a particular category of the systematization: $(\mathcal{A}^i \oplus \mathcal{R}^j)$, with $i, j \in \{2,3\}$ reading:

- $\mathcal{A}^i$: selected attributes are visualized using i-dimensional graphical elements,
- $\mathcal{R}^j$: the reference space is visualized using j-dimensional graphical elements.

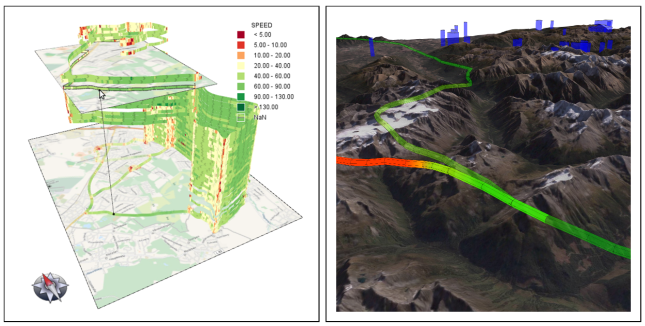
Figure 1 shows an overview of the categorization based on this systematization. The horizontal axis shows exemplary manifestations of 2D and 3D presentations of the spatial reference (e.g., map or terrain), while the vertical axis shows exemplary manifestations of 2D and 3D presentations of the attribute space (data values).

Based on the proposed systematization, existing visualization techniques can be categorized as either $(\mathcal{A}^2 \oplus \mathcal{R}^2)$, $(\mathcal{A}^2 \oplus \mathcal{R}^3)$, $(\mathcal{A}^3 \oplus \mathcal{R}^2)$ or $(\mathcal{A}^3 \oplus \mathcal{R}^3)$. Figure 2 shows exemplary instances for each category. In general, the techniques of one category share common characteristics. Comparing these characteristics helps us to understand implications of using a 2D or 3D presentation of the attribute space and the reference space.

$(\mathcal{A}^2 \oplus \mathcal{R}^2)$ Presentations, such as 2D maps (Fig. 2(a)), have a long tradition. The data values are presented by 2D graphical elements directly within the 2D presentation of the reference space. For a 2D output medium no projection of elements is needed, and if the number of data values does not exceed the available display space, no occlusion occurs. However, in case of a geo-spatial reference space distortions can appear, because the surface of the earth is curved and uneven, although these might be noticeable only on larger scale.



(a) $(\mathcal{A}^2 \oplus \mathcal{R}^2)$ (b) $(\mathcal{A}^2 \oplus \mathcal{R}^3)$



(c) $(\mathcal{A}^3 \oplus \mathcal{R}^2)$ (d) $(\mathcal{A}^3 \oplus \mathcal{R}^3)$

Figure 2: Exemplary visualization techniques for each category of the proposed systematization, showing (a) 2D diagrams on a 2D map [23], (b) 2D diagrams on billboards and 3D ocean floor [39], (c) 3D stacked trajectories over a 2D map [57], and (d) 3D trajectory in 3D terrain (created with our software).

$(\mathcal{A}^2 \oplus \mathcal{R}^3)$ The presentation of the attribute space in 2D and the reference space in 3D allows not only to present the data values in a given 3D spatial context, but also enables the user to explore and understand the structure of a 3D reference space. In the example in Figure 2(b), hydrological data is depicted above the ocean floor. The visual complexity of the complete presentation is limited by using only 2D graphical elements to encode the data values. Still, as soon as 3D is used, occlusion becomes a problem. Hence, only a subset of data is visible.

$(\mathcal{A}^3 \oplus \mathcal{R}^2)$ Data values can also be presented in 3D, while the underlying spatial reference is shown in 2D. For instance, the shown stacked trajectories in Figure 2(c) are located above a planar map to visualize the spatial reference. This allows us to use the third dimension to encode other information different from height (e.g., time). This increases the complexity of decoding the visualization, but can facilitate overview.

$(\mathcal{A}^3 \oplus \mathcal{R}^3)$ Presenting data values in 3D, with a 3D depiction of the spatial reference allows for a natural perception of the attribute space's structure (e.g., distribution, extend and correlation) as well as the reference space (e.g., shape). For instance, in Figure 2(d) a presentation of flight paths through thunderstorm cells above a digital terrain model is shown. However, when using $(\mathcal{A}^3 \oplus \mathcal{R}^3)$, a high density of data values increases the possibility of occlusion.

The following section discusses each category in more detail, by examining existing visualization techniques and pointing out challenges, problems, and possible solutions.

(a) (b)

Figure 3: Exemplary $(\mathcal{A}^2 \oplus \mathcal{R}^2)$ visualization techniques, showing (a) weather attributes [63], and (b) aggregated movements [4] on a 2D map.

3 Examples and Discussion

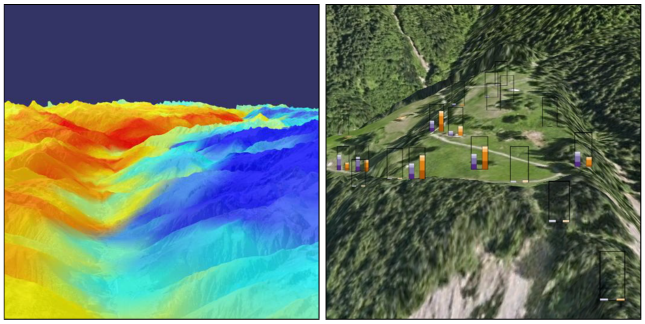
To illustrate the systematization and to highlight characteristics and differences, we chose weather visualization as a common example for all four categories. Furthermore, we selected additional exemplary visualization techniques for spatial data. Our discussion focuses on fundamental properties of these visualization techniques to emphasize the key factors of 2D and 3D attribute and reference presentations. This way, we aim to show how our systematization approach can deepen the understanding of advantages, disadvantages, and implications of visualization designs.

3.1 $(\mathcal{A}^2 \oplus \mathcal{R}^2)$ Characteristics

The 2D presentation of attribute values in a 2D depiction of the reference space has a long history with many established systems and application areas. Among the data presentations of this category are numerous well-known and widely-used visualization techniques, such as cartographic maps showing public transport systems or agricultural land use. Such visualizations are solely constructed from 2D graphical elements. Hence, generally no projections or visibility computations are required to display them on a 2D output medium. In addition, appropriate design and layout of graphical elements help to prevent occlusions. Consequently, data values can be easily read from uniform 2D displays, making such presentations particularly effective.

Two-dimensional weather visualizations have a likewise long history and are an inherent part of our everyday lives. Figure 3(a) shows an example of such a weather display of a recent design study [63]. In this visualization approach, multiple weather attributes, such as temperature, atmospheric pressure, and wind speed, are depicted on top of a geographic map. The geographic reference space is shown by lines marking state borders. The attribute space is densely encoded by several distinct graphical elements, including color textures, isolines, and animated wind traces. In this form of presentation, the multivariate weather attributes can be directly viewed in their spatial context and the 2D presentation style facilitates a clear examination of visual variables. However, the number of perceivable elements in such a 2D display is limited. Hence, a large number of attributes and observation points require a careful visual design. Yet, it might still be difficult to encode them in a single image, because too many graphical elements can easily result in *visual clutter*, making the identification of single objects as well as general patterns hardly possible [19, 22].

One approach to address these problems is to utilize the concept of cartographic generalization, such as graphic or conceptual generalization [38]. In [4], a spatial generalization method is applied to massive movement data to abstract from single objects and to simultaneously show representative trends in the data (see Fig. 3(b)).



(a) (b)

Figure 4: Exemplary $(\mathcal{A}^2 \oplus \mathcal{R}^3)$ visualization techniques, showing the use of (a) 2D texture maps [50] © Atlas der Schweiz 2012, and (b) 2D billboards [9] in a 3D digital terrain model.

However, the loss of certain aspects, such as specific details or outliers, is a disadvantage of the generalization process.

Another approach is to combine multiple attributes or temporal changes to design more complex diagrams and to show them only at selected observation points in the depiction of the reference space (cf. [3, 38, 1]). For instance, iconographic displays, such as glyph packing [37] or stick figures [44], are common tools for visualizing multivariate attributes in spatial data sets [24]. The observation points are typically selected on a 2D grid and the attribute space is mapped to a distribution of different icons or glyphs according to the attribute values at each grid point. Such presentations typically use visual variables, such as orientation, size, and shape, to encode certain aspects of the attribute and reference space. Since a perspective projection of graphical elements is generally not required and therefore no *distortions* occur, these representations can be accurately decoded. Further exemplary $(\mathcal{A}^2 \oplus \mathcal{R}^2)$ visualization techniques can be found in [47, 49, 53, 25].

However, $(\mathcal{A}^2 \oplus \mathcal{R}^2)$ has limitations in the way the data can be presented. Utilizing a third display dimension for the presentation of the attribute or reference space often allows for diverse extensions of 2D visualizations. Next, we investigate such visualization designs and outline the corresponding properties and implications.

3.2 $(\mathcal{A}^2 \oplus \mathcal{R}^3)$ Characteristics

The 2D presentation of attributes in a 3D depiction of the reference space enables several distinct approaches to visualize spatial data. Visualization techniques of this category are constructed by combining 2D and 3D graphical elements. Consequently, projections and visibility computations are partially required for the display on a 2D output medium.

The reference space is visualized using three display dimensions, which allows to represent a 3D spatial context in its full extent. For example, in visualization of geo-spatial data, the third dimension is typically used to depict virtual 3D models (e.g., digital elevation models), usually aiming for a less abstract presentation compared to 2D maps. Furthermore, such presentations of the reference space can support the interpretation of 3D spatial relationships, such as the occurrence of attribute values in correlation with specific landscape characteristics, e.g., mountains or valleys. In numerous application areas, such as flight simulation or virtual city tours, a 3D depiction of the spatial context is beneficial for interaction tasks and to communicate the data effectively. The presentation of the attribute space is assembled from 2D graphical elements, e.g., 2D textures mapped onto the 3D representation of the reference space or 2D billboards (see Fig. 4(a) and Fig. 4(b) respectively).

In [50], texture mapping is used to visualize precipitation data in a 3D terrain model (see Fig. 4(a)). The precipitation values are encoded using a continuous multi-hue color scale and are mapped onto the terrain using a 2D surface texture. Such visualization designs allow a consistent display of attribute values at every point in the presentation of the reference space. However, it is crucial that the raster data has a sufficient resolution and that appropriate filtering methods are used to prevent texturing artifacts, such as stretching or aliasing. Such artifacts may result in undefined visual representations and can lead to misreadings of attribute values. Similarly, the lighting and shading of the spatial context can influence the expressiveness of presentations with color-coded attributes [21]. The introduced variations in brightness can impair the perception of colors and thus the identification of encoded values. Still, lighting is often necessary to communicate the spatial structures of the reference space.

In [9], the attribute space is encoded using 2D graphical elements mapped onto billboards (see Fig. 4(b)). The mapped representations can range from icons to complex diagrams. They are typically placed at selected observation points and always face the viewer to counteract perspective distortions and orientation problems. However, the interpretation of such presentations might still be affected by perspective foreshortening, making the content of billboards near and far from the viewer comparable to only a limited extent. Furthermore, the spatial affiliations of the graphical elements must be clearly identifiable. Especially, if the attribute presentations are placed with a distance to corresponding observation points, additional visual links, such as lines or appropriate color codes, are required to establish the associations.

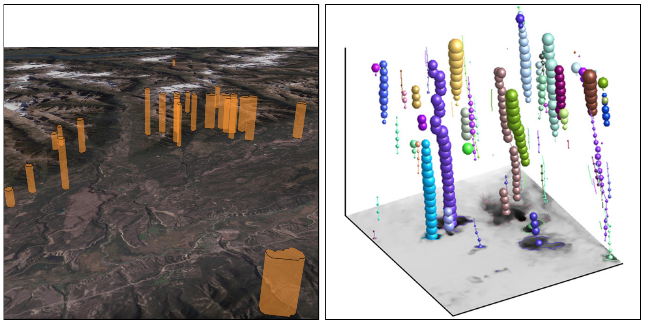
A general challenge for visualization techniques of this category is occlusion, caused by the 3D depiction of the spatial reference. For example, with 2D attribute presentation on 3D virtual globes only half of the data is visible at any given time [54]. Likewise, near-surface perspectives in presentations of geo-spatial data sets usually involve a high ratio of occluded elements. Hence, suitable interaction techniques or other enhanced methods (see Sec. 4.1) have to be considered for an effective data visualization. Other $(\mathcal{A}^2 \oplus \mathcal{R}^3)$ examples can be found in [10, 33, 36, 65].

Besides 3D presentations of the reference space, the third display dimension can also be used to encode specific aspects of the attribute space. Such designs offer several alternative visualization approaches for spatial data, which we explore in the remaining categories beginning with the next section.

3.3 $(\mathcal{A}^3 \oplus \mathcal{R}^2)$ Characteristics

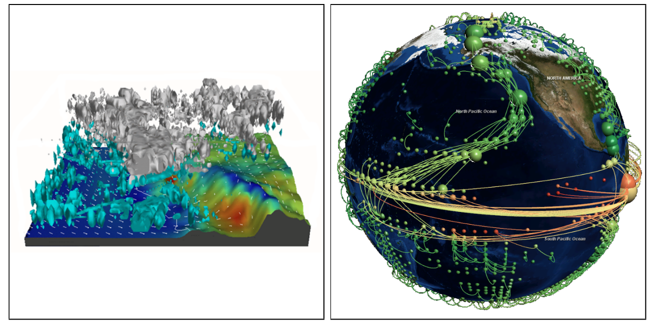
Three-dimensional graphical elements can be used to depict the attribute values, whereas the reference space is presented, using 2D graphical elements. While typically the reference space is depicted by a map, the presentation of the data values ranges from 3D bar charts and glyphs to trajectories and more complex objects. Generally, 3D graphical elements can be utilized to encode multiple attributes. For instance, the size [60] and the shape [42] of icons can be used to visualize the values of two different attributes. Such a design requires a careful consideration of human vision and perception. Additionally, distributing graphical elements within a 3D presentation space, can help to improve the overview and decrease visual clutter. Yet, as in all 3D presentations, occlusion of data values remains a problem.

$(\mathcal{A}^3 \oplus \mathcal{R}^2)$ weather visualizations are not as widely used as $(\mathcal{A}^2 \oplus \mathcal{R}^2)$ presentations. However, especially in scientific meteorological analysis, data have often a large number of attributes. To visualize these attributes, 3D data presentations can be helpful. Two typical weather visualization techniques are shown in Figure 5. The geo-spatial reference in Figure 5(a) is presented using an oblique view onto a 2D map textured with satellite images. The data values are depicted above the presentation of the reference space. The attributes, here thunderstorm cells, have only a two 2D extend, but the shapes are extruded along the z-axis to form 3D prisms. The z-coordinates are used to encode the severity of each particular cell.



(a) (b)

Figure 5: Exemplary $(\mathcal{A}^3 \oplus \mathcal{R}^2)$ visualization techniques. (a) Abstract shapes, symbolizing extend and form of thunderstorm cells (x, y coordinates) and their severity (height) (created with our software). (b) Space-time events of precipitating clouds, depicted by spheres of varying radii [60].



(a) (b)

Figure 6: Exemplary $(\mathcal{A}^3 \oplus \mathcal{R}^3)$ visualization techniques. (a) Isosurfaces representing different types of clouds above the coastline of California [7], and (b) visualization of climate networks on a 3D virtual globe [54].

This allows for a good overview of the location and extend of the data. But perspective projection of the 3D elements leads to distortions that might influence the readability and measurability of the attribute values [32].

To avoid such problems, an orthographic projection can be utilized. But as a result, the depth perception decreases as well as the amount of data that can be depicted simultaneously. Moreover, accurately determining the location of data values within their spatial reference becomes a difficult task. A large distance in screen-space between graphical elements presenting the attribute space and elements presenting the reference space increases this problem. Turdukulov et al. [60] visualize precipitating cloud event data (Fig. 5(b)), where the z-axis (height) is used to encode the time of each event. The later an event occurs, the higher it is presented above the base and the more difficult is the perception of the spatial assignment. This is a general problem. In this specific technique, color contours are used to highlight the spatial location of each object. Other techniques use shadow casting or connecting lines between the object and the reference space to engage this problem.

Using the z-axis to encode a specific attribute is a typical approach (Fig. 5(b)). An often applied method is to map time to height, which leads to a space-time cube [27]. The simultaneous presentation of space and time can facilitate visual analysis by showing not only spatial, but also temporal correlations. This concept was recently thoroughly reviewed by Bach et al. [5]. Further exemplary $(\mathcal{A}^3 \oplus \mathcal{R}^2)$ visualization techniques can be found in [31, 56, 26, 55].

Still, often the 3D characteristics of the reference space have to be communicated alongside the data values. Thus, $(\mathcal{A}^3 \oplus \mathcal{R}^3)$ presentations are used as is discussed in the next section.

3.4 $(\mathcal{A}^3 \oplus \mathcal{R}^3)$ Characteristics

A 3D presentation of the attribute and reference space enables an intuitive perception of the 3D shape and extend of data values, as well as the structure of the underlying spatial context. Moreover, 3D spatial distributions are communicated effectively. However, as for every 3D presentation, a high density of data leads to occlusion. Through appropriate abstraction, filtering, and aggregation of data values, effective 3D presentations can be designed. Yet, this is a challenging process that depends on the characteristics of the data as well as the visualization context.

Three-dimensional weather visualizations are typically used to analyze and forecast the distribution of meteorological phenomena, such as clouds or airflows, which are often a result of simulations. Bennett et al. [7] use 3D isosurfaces to visualize the 3D extend of cloud ice (white) and cloud water (blue) (Fig. 6(a)). The volumetric nature of this specific data results in rather large occluders, that hinder the communication of parts of the data [20].

A typical approach is to use transparency. However, with transparency the fore- and background cannot be distinguished well. Therefore, transparency should be used carefully to reduce ambiguity of color and structure.

Tominski et al. [54] visualize global climate network data (Fig. 6(b)). The presentation of the reference space using a virtual globe allows the visualization of structural coherences without discontinuity and the 3D presentation of the network data shows less visual clutter than a typical 2D presentation. Additionally, the third dimension increases the flexibility of designing the layout of the network and reduces partly the occlusion of connections and nodes. However, since the network is shown with respect to the virtual globe, only attributes on one hemisphere are visible.

Other applications of $(\mathcal{A}^3 \oplus \mathcal{R}^3)$ presentations are flow visualizations, e.g., 3D visualizations of hurricanes [64]. Such visualizations can communicate the structure and spatial correlation of 3D spatial data especially well, since no projection into the 2D presentation space is needed. Hence, a good comprehension of shape and extend of data can be achieved. Further $(\mathcal{A}^3 \oplus \mathcal{R}^3)$ examples are [59, 62, 68, 16].

3.5 Summary

In this chapter we discussed typical visualization techniques for each category of the proposed systematization. The properties are summarized in Table 1. For each property its general occurrence is marked by $\bullet$, while the absence is marked by $\circ$.

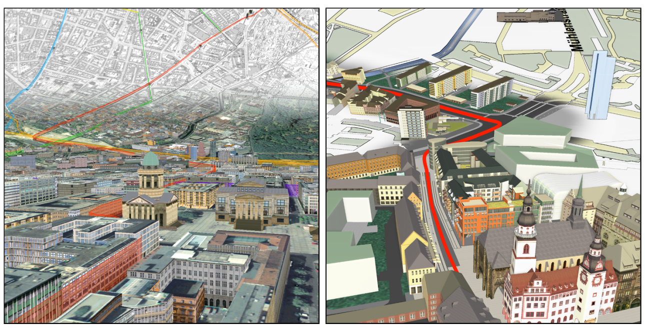
Considering the selected properties, the four categories can be characterized by the occurrence of distortion and occlusion, which arise naturally, when using 3D either for $\mathcal{A}$ or $\mathcal{R}$. This also implies that visual variables representing the attribute values can be distorted. Moreover, matching the spatial location of elements of the attribute space to their reference can be difficult when 3D is used. On the other hand, the comprehensive presentation of 3D spatial structures and distributions of elements of $\mathcal{A}$ and $\mathcal{R}$ is an advantage of 3D presentations. Also the number of perceivable graphical elements can be increased, when the attribute space is presented in 3D.

This categorization is a first step towards a better comprehension of characteristics and implications regarding 2D and 3D visualization of spatial data. For a more detailed statement on the degree of occurrence or other forms of quantization, a more thorough review and categorization of existing techniques is required. However, this would by far exceed the scope of this work.

In the next chapter we point out potential enhancements of the proposed systematization and present research steps for future work.

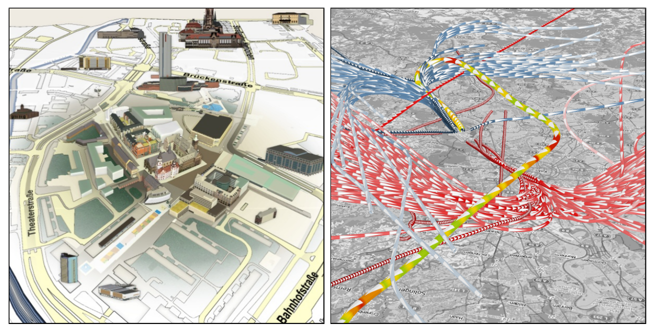
Properties	$(\mathcal{A}^2 \oplus \mathcal{R}^2)$	$(\mathcal{A}^2 \oplus \mathcal{R}^3)$	$(\mathcal{A}^3 \oplus \mathcal{R}^2)$	$(\mathcal{A}^3 \oplus \mathcal{R}^3)$
No occlusion of $\mathcal{A}$ by $\mathcal{R}$	•	○	•	○
No self-occlusion of $\mathcal{A}$	•	○ (Billboards), • (Texturing)	○	○
No occlusion of $\mathcal{R}$ by $\mathcal{A}$	○	○	○	○
No self-occlusion of $\mathcal{R}$	•	○	•	○
Perspective distortion of $\mathcal{A}$	○	○ (Billboards), • (Texturing)	•	•
Perspective distortion of $\mathcal{R}$	○	•	•	•
Preservation of geometric properties (e.g., size, orientation, shape) of $\mathcal{A}$	•	○	○	○
Preservation of color properties (e.g. hue, value, saturation) of $\mathcal{A}$	•	• (Billboards), ○ (Texturing)	•	•
Presentation mapping preserves 2D spatial structure of elements in $\mathcal{A}$	•	•	•	•
Presentation mapping preserves 3D spatial structure of elements in $\mathcal{A}$	○	○	•	•
Representability of 2D spatial distribution of elements in $\mathcal{A}$	•	•	•	•
Representability of 3D spatial distribution of elements in $\mathcal{A}$	○	○	•	•
Matching presentation of elements of $\mathcal{A}$ to $\mathcal{R}$	•	○ (Billboards), • (Texturing)	○	○
Using third dimension to encode attributes	○	○	•	•
Scalability of number of perceivable graphical elements	○	○	•	•

Table 1: Overview of the identified characteristics of 2D and 3D presentation of the attribute space ($\mathcal{A}$) and 2D and 3D presentation of the reference space ($\mathcal{R}$). The table shows the occurrence (•) or absence (○) of general properties for each category of our systematization.



(a) (b)

Figure 7: (a) Multi-perspective views show transitions between 2D and 3D presentations of the reference space [41], while (b) shows transitions between a 2D and 3D presentation of the attribute space [43].



(a) (b)

Figure 8: (a) Presentation of a non-photorealistic rendered city model [48], and (b) animated trajectories with varying color and texture in 3D [11].

4 Enhancements and Future Trends

The proposed systematization was used to categorize selected visualization techniques and to identify general properties as well as specific characteristics. However, until now the discussion only focused on fundamental and clearly distinguishable aspects to highlight the similarities and differences between the four categories. This section demonstrates how the systematization can be extended and combined with other types of categorizations that focus on presentation characteristics. Moreover, we present directions for future research.

4.1 Enhancements

So far, our examples were discussed according to the four discrete categories of our systematization. In this section we also consider visualization techniques that are mainly based on *transitions* between 2D and 3D presentations of the attribute and reference space. Furthermore, additional presentation criteria are taken into account as concluding remarks.

2D and 3D Transitions. The question whether to use 2D or 3D presentations implicates different advantages and disadvantages. However, there are approaches that combine 2D and 3D presentations to utilize individual benefits and to counteract respective drawbacks. Figure 7(a) shows an example of multi-perspective views, which depict the reference space both in 2D and 3D [41]. Based on global deformations, they partially reduce occlusion and increase screen-space utilization by bending the virtual 3D terrain model up- or downwards while the elements of the attribute space (virtual 3D buildings) remain unchanged. Similarly, Figure 7(b) extends the previous approach by enabling seamless transitions between 2D and 3D presentations of virtual 3D buildings [43]. Here, graphical elements, which are near to the view point, are depicted in detail using 3D, while those further away and not in the focus of the viewer are presented in 2D.

Additional Presentation Criteria. Beyond focusing on the dimensionality of the presentation with respect to the attribute and reference space, a major aspect in visualization is the style of the presentation itself. This includes the presentation of the attribute and reference space in a realistic or abstract way (PR vs. NPR) as well as the static or dynamic depiction. Such criteria can be used to extend the proposed systematization by additional categories.

In principle, presentations based on photorealistic or non-photorealistic rendering techniques [52] can be distinguished, yielding different level-of-abstractions. Using such techniques for the depiction of selected attributes or the spatial context facilitates a number of applications, e.g., visualization of data outliers or focus+context visualization. For instance, in [48] different rendering styles are used to guide the focus of the viewer to prioritized information (see Fig. 8(a)).

As another aspect, the presentation of the attribute and reference space can be either static or dynamic. However, animated graphical elements are most frequently used to visualize attribute values, which change over time. Hence, animated presentations are typically used in spatio-temporal visualization, making dynamic depictions of attributes in a static spatial context (e.g., 2D maps or 3D digital terrain models) a standard technique in digital cartography [30]. Figure 8(b) shows an animated 3D presentation of the attribute space to visualize massive air-traffic trajectories over a static 2D map [11].

4.2 Future Work

When planning a visualization, designers are confronted with a number of design choices. Particularly, the basic question whether to use 2D or 3D for data visualization raises the following challenges for the data visualization community: (1) How can we decide which existing visualization technique is more suitable for certain data sets or tasks, and (2) how do we compare existing visualization techniques to identify their individual advantages and disadvantages. To reduce the workload of visualization engineers and to support the design process, future development of design guidelines for decision support can be valuable.

With our systematization and the identification of the initial properties in Table 1, we take a first step in this direction. It facilitates problem understanding and can form the basis of a more detailed discussion of the topic. However, the current systematization does not account for other aspects such as interaction techniques, data complexity, and the run-time complexity of the image synthesis process (rendering), which in turn also influences the choice of visualization techniques. In addition to extending the list of properties for comparison of visualization techniques, the currently used binary categorization can be enhanced to more sophisticated qualitative assessment of visualization techniques. For this purpose, appropriate evaluations are needed. Furthermore, user studies are required to validate the applicability of our approach.

Previous user studies related to the evaluation and comparison of 2D and 3D visualization techniques often do not lead to significant results or clear conclusions [14, 9, 51, 18]. This suggests that considering only dimensionality of the complete presentation, without distinguishing between attribute and reference space, is probably too general. With respect to this, a direction for future work could be the review and redesign of existing 2D vs. 3D user studies while considering the four categories of our systematization.

5 Conclusion

For spatial data, the question whether to use 2D or 3D presentations is difficult to answer. Therefore, the proposed systematization advances the discussion by distinguishing between 2D and 3D presentations of both, the attribute and reference space. By categorizing existing visualization techniques, we identified fundamental characteristics. These characteristics can serve as a base for better comprehension of advantages, drawbacks, and implications of 2D and 3D presentations. Hence, this systematization is a first step towards decision support for an effective visualization design.

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