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A Survey of Multi-Dimensional Data Visualization using Different Projection Techniques

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ABSTRACT

The features of a multi-dimensional dataset are the critical parts for visualizing the data in the form of a projected 2D display. A dataset contains different features, where limited features can be effectively interpreted and visualized. But if the dimension increases, then it becomes difficult to analyse and predict. In this paper, a detailed survey is proposed where commonly used projection methods are used in different works. In this survey, different comparisons are also used for existing works based on different features and parameters. Moreover, it also discusses the limitations and strong points of the works. Finally, this article serves as a valuable guide to new researcher and reader in the area of data visualization. It also provides a comprehensive understanding of different data visualization techniques along with their advantages and disadvantages.

KEYWORDS

Multi-Dimensional Data; Data Visualization; Dimensionality Reduction; Projection Techniques; Visual Analytics

1. INTRODUCTION

In the last few decades, the applications of data visualization have increased rapidly in terms of several uses and applications [1]. Traditionally, single modality is used in the applications, but due to rapid changes in technology, data collection methodologies change and a multimodal environment has emerged for data utilization [2]. There are several studies that propose numerous methods where different types of attractive visualizations are used to represent research outcomes [3-6]. There are several outcomes of data visualization that are shown in Fig. 1. Each of the outcomes is used in any given real-life application. Day by day, it is rapidly used everywhere, and it helps to represent ambiguous and complex information in an easier way. Some of the applications are shown in Fig. 2.

In fact, the applications of data visualization differ with the context of several graphical usages. Graphical methods such as pie charts, bar charts, line graphs, histograms, boxplots, and scatterplots are widely used due to their simplicity and effectiveness for low-dimensional data [7]. However, their representational power is generally limited to one, two, or three variables at a time, restricting their ability to reveal intricate, multidimensional relationships. So, it creates several issues and challenges that are shown in Fig. 3. These challenges affect accuracy and effectiveness in business, education, research, etc., for data processing and handling [8]. So, inaccurate, incomplete, and inconsistent data and information create misleading visuals. Sometimes, inappropriate selection of chart, layout, label, color, and annotation also creates difficulties, bias, and misinterpretation [9-10].

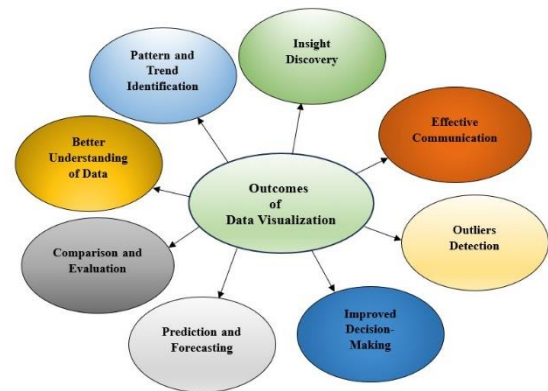


Fig. 1 Several outcomes of data visualization.

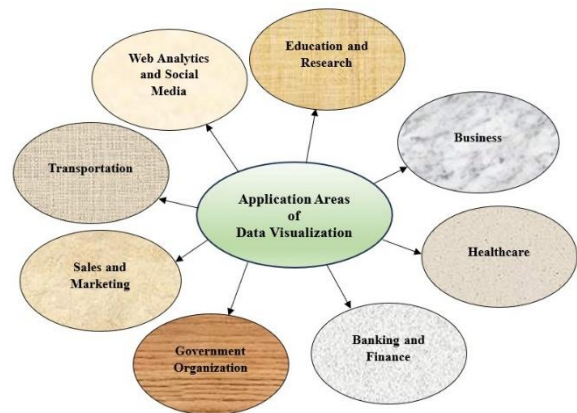


Fig. 2 Different application areas of data visualization.

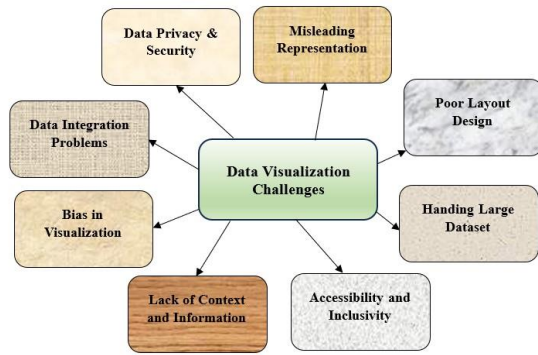


Fig. 3 Challenges of data visualization.

1.1. Motivation

In the last few years, multi-dimensional data has increased rapidly in different areas such as healthcare, business, finance, and different cutting-edge areas. The purpose of the project-based visualization is to represent a complex dataset in a lower dimensional space. There are several techniques that have already been proposed in different domains. But each of the techniques varies in application scope, scalability, and effectiveness. This survey aims to provide new researchers and readers with a systematic and comprehensive review of multi-dimensional data visualization techniques. It categorizes existing methods, analyses their strengths and limitations, and highlights future research directions.

1.2. Contributions

The major contribution of this survey is mentioned as follows:

- A comprehensive literature review is done for existing visualization methods.
- All the reviewed articles are studied and systematically classified into four categories.
- A detailed comparative analysis is completed with traditional visualization methods
- A detailed comparative analysis is done for some existing methods based on certain parameters.

1.3. Organization of the paper

Section 2 discusses existing works based on projection and dimensionality reduction techniques. Section 3 discusses existing works based on interactive visualization and visual analytics. Section 4 discusses existing works based on visualization design and rendering techniques. Section 5 discusses existing works based on domain-specific applications. Section 6 discusses comparative analysis of different visualization techniques. Section 7 concludes the paper with future research directions.

2. PROJECTION AND DIMENSIONALITY REDUCTION TECHNIQUES

In the recent few years, several studies have been proposed in the areas of projection and dimensionality reduction techniques. Some of the works are discussed in this section. M. Cuesta et al. [11] proposed a method for high-dimensional datasets to support class separability. The name of the method is CSViz, which indicates class separable visualization. It is a novel visualization method that is used to overcome the issue of visualization labelled with the help of visualization analytics. Finally, the proposed method is simulated and analysed based on 50 datasets with different features. T. Xiao et al. [12] proposed a method for a social network service to support a document embedding system and topic transition visualization. It analyses the abstract of the document based on two-dimensional space. The visualization of the work uses time series analysis for word analysis. Finally, it analyses different data such as user ratings, COVID-19 data, and nuclear disaster data. M. Shi et al. [13] proposed a method for unsupervised learning that is fusion of temporal reasoning and structural learning. The main purpose of this method is compact feature analysis based on similarity subspace analysis. Finally, it compares with several streams of video for 2D analysis using an unsupervised learning technique. It outperforms the existing method for different attributes. V. Molchanov and L. Linsen [14] proposed a method for preserving shape in star coordinates. In this method, all dimensions are explored within the whole set of attributes. Analysis tasks detect clusters trends and outliers. The method focuses on minimizing loss of visualization related information. In this paper, the authors used 2D visual space technique along with an encoding method for mapping more than one-dimensional data. It improves the tool for exploration by linear mapping. A different color scheme is used for visualizing membership information. M. Y. Huh and K. Kim [15] proposed a method for data visualization in multi-dimensional data. The method is named as Grand Tour technique. It helps to change 2D projection of the data and illustrates several structures and patterns. Finally, it helps to avoid unused motion and enhance the clarity and interpretability of the visualization. The summarized description of the above-mentioned methods is shown in Table 1.

Table. 1 Review of Projection and Dimensionality Reduction.

Ref.	Year	Used Technique	Main Contribution	Limitations
[11]	2024	CSViz visualization	Class separability in multi-dimensional data	Performance issues in very large data
[12]	2023	Embedding + dimensionality reduction	Topic transition visualization in SNS	Limited interpretability
[13]	2022	Unsupervised DR model	Structural + temporal	Accuracy trade-off

[14]	2018	Star coordinates	correlation learning Shape-preserving visualization	Limited flexibility
[15]	2002	Modified Grand Tour	Better visualization of multi-dimensional data	Hard to interpret, computationally heavy

3. INTERACTIVE VISUALIZATION AND VISUAL ANALYTICS

In the last few years, numerous works are proposed based on interactive visualization and visual analytics. Some of the works are discussed in this section. Su et al. [16] designed an interactive visualization tool named as G2 for a web-based analysis framework. The framework is used for uniform set interaction for authoring purposes. There are several applications of ready-to-use features based on experience, declarative interaction, event support, customization flexibility, and layout optimization. Finally, it improves the visual interaction by improving efficiency and flow of interaction. M. Fan and L. Zhou [17] proposed a method for medical visualization aimed design purposes. The proposed method consists of cognitive habits and analytics logic for distinguishing among the design, target user analysis, and classifying the task based on descriptive analysis. Finally, it analyses three models of medical visualization. L. Ji et al. [18] proposed a method for visual exploration based on an industrial dataset. It is based on the fusion of multi sensor dataset high dimensional pattern. It constructs a visual framework for canonical correlation pattern that uses multi-level exploration and multi-perspective pattern. Finally, the result outperforms different patterns with correlation for visual comparison. F. Hong et al. [19] proposed a method for ensemble data aimed visual analytics. The main purpose of this work is to realize set analysis with large-scale data. It is also used to find relation among data. It helps to design two-dimension matrix for ensemble data. The visualization contains similar feature in subspace for each intersection. Y. Wu et al. [20] proposed a method for statistical visualization where size of the data is large. It is an adaptive method based on data where statistical analysis is used for graphics processing units. It uses a Gaussian mixture model for scientific analysis for real-world applications. The result is analysed iteratively through computational analysis for high-quality reconstruction. G. Wu et al. [21] proposed a method for visual analysis in the context of damage data from simulations. It uses an integrated visual method for defect analysis as clustering and identification and graph tracking. It overcomes the issue of blur modes and defect dynamics in the visualization. Juri F. Buchmüller et al. [22] proposed a method spatial rug for compact visualization. It analyses the data movement based on parameters of time and space. The work is based on a custom color mapping method to visualize large-scale data efficiently. The proposed method is used to encode spatial features to enable related space and enhance the features in the dataset. J. Li et al. [23] proposed

a method for geoscience data analysis which is based on interactive visualization. The work is based on more than one parameter with a time series analysis dataset. It contains observation-based subset selection by a domain expert. It illustrates high-level analysis in compact view mode. The spatial information consists of attribute and temporal aspect for center visualization. P. Ertl and B. Rohde [24] proposed a method for molecule cloud aimed at compact visualization purposes. The proposed method is used to represent common feature analysis for chemical datasets in the form of a cloud format. Additionally, the method also shows biological correlation of the molecules based on color coding. The methodology designed by S. Ferré et al. [25] is used for a multi-dimensional cube. It helps to organize different subsets of the cube with the help of a query. It provides the set of navigation based on structured dimension. Finally, it describes several representations such as multi-value context, sets of objects, aggregate value, etc. The summarized description of the above-mentioned methods is shown in Table 2.

Table. 2 Review of Interactive Visualization and Visual Analytics.

Ref.	Year	Used Technique	Main Contribution	Limitations
[16]	2026	A framework is used for Web-based visualization	Customizable interactive visualization technique	It is not suitable for large datasets
[17]	2025	Design study model	Process model for medical visualization	Domain-specific applicability
[18]	2024	Multi-sensor fusion visualization	Industrial dataset correlation exploration	Complex implementation
[19]	2024	Coupled subspace analytics	Ensemble data visualization	High computational complexity
[20]	2023	GPU-based reconstruction	Large-scale statistical visualization	Requires specialized hardware
[21]	2022	3D defect clustering visualization	Analysis of irradiation simulation data	Domain-specific
[22]	2021	SpatialRugs technique	Compact spatio-temporal visualization	Limited scalability
[23]	2017	Interactive visualization	Geoscience data exploration	Dataset-specific
[24]	2012	Molecule cloud visualization	Compact chemical data representation	Limited scalability
[25]	2012	Concept cubes	Multi-dimensional data exploration	High dimensional complexity

4. VISUALIZATION DESIGN AND RENDERING TECHNIQUES

In the last few years, several works have been proposed in the area of visualization design, perception and rendering techniques. Some of the works are discussed in this section. C. Kelleher and A. Braswell [26] designed and illustrated a recommendation approach for an introductory overview based on data visualization. The visualization method is designed for scientific data visualization with respect to a

large set of data. The main reason behind this is the rapid growth of large sets of data along with big data. The work preserves complex data visualization in multiple dimensions. Finally, the work outperforms static visualization with interactive visualization using animation. K. B. Schloss et al. [27] proposed a method for colormaps to support data visualization. In this method, the colormaps were influenced by relations between colors within colormaps and colors of the background. The proposed method analysed color quantity mapping to map colors in data visualization and helps to resolve several conflicts of data visualization. In [28], the authors analysed the color assignment for optimization purposes. It is based on visual separability for strong influence. It is also based on a multi-class structure that uses the visualization method of scatter plots. The method used a genetic algorithm to optimize good color assignment. J. Jo et al. [29] proposed a model where multiclass maps, scatter plots (multidimensional projections thematic geographic maps), and categorical attribute is rendered using shape or color. The methodology of this work is a map visualization method. It illustrates a vast range of multi-class visualization density map. It illustrates only two attributes based on a quantitative approach. The attributes are mapped in two axes, X and Y. The methodology is based on a web application that runs on a web browser to configure and analyse the data. A. Sarikaya and M. Gleicher [30] proposed a survey for scatter plot analysis that helps the designer make choices in the visualization. It includes several design decisions that highlight different features. Three basics are connected in this survey, such as design choice, data features and analysis tasks. Based on this survey, it overcomes the limitation of traditional scatterplots. R. A. Rensink and G. Baldrige [31] proposed a perception method for scatterplots. The method analysed the visual perception correlation based on classical psychophysical techniques. The accuracy is measured by parameters of scatterplots for lower and upper values. Finally, it outperforms the result based on visualization. The early origins methodology designed by M. Friendly and D. Denis [32] for analysing scatter plots in the visualization. This paper traced several developments of the scatter plot in the history. It also discussed modern inheritors and recommend it unique benefits. It includes several graphical components to enhance the quality of the visualization including annotation. The summarized description of the above-mentioned methods is shown in Table 3.

Table. 3 Review of Visualization Design and Rendering Techniques.

Ref.	Year	Used Technique	Main Contribution	Limitations
[26]	2021	Visualization guidelines	Handling large environmental datasets	Conceptual (no system)
[27]	2018	Colormap design	Mapping color to meaning	Limited adaptability
[28]	2018	Color optimization	Improved class separability	Not suitable for all datasets
[29]	2018	Declarative rendering model	Multiclass density visualization	Complexity in implementation

[30]	2017	Scatterplot design framework	Defines tasks and improves scatterplot understanding	Only 2D data, no multi-dimensional handling
[31]	2010	Scatterplot perception analysis	Understanding correlation perception	No automated system
[32]	2005	Historical analysis of scatterplots	Explains evolution and origin of scatterplots	Not modern or computational, descriptive only

5. DOMAIN-SPECIFIC APPLICATIONS

In the area of domain-specific application and survey studies, several works have been proposed in the last few years. Some of the works are discussed in this section. T. Houichime and Y. Amrani [33] proposed a method for call graphs that used pattern detection and visualization. It helps in dynamic warping and data profiling for data visualization. The framework of the proposed method is divided into two parts. First part is used to visualize runtime data. The second part is a visualization for symbolic sequencing in the pattern. It also helps to analyse the classification process, optimal length, and symbolic and compact translation. W. Wu et al. [34] proposed a visualization method for family classification and imbalanced analysis. The method is based on malware visualization that uses matrix suitability and transition probability analysis. The CNN model is used for input image analysis and prediction. Finally, it outperforms the results in the context of classification and compatibility. M. Du et al. [35] proposed a review for enhancing financial literacy using data visualization. The review is based on a total of 37 studies based on question evaluation, history, pedagogy motivation and technology. The review consists of time and space-based visualization, analysis of visualization tools, and addressed different topics of financial, evaluation and intervention of teaching effectiveness. The outcomes help guide to the researchers and students. The summarized description of the above-mentioned methods is shown in Table 4.

Table. 4 Review of Domain-Specific Applications.

Ref.	Year	Used Technique	Main Contribution	Limitations
[33]	2026	Runtime profiling + dynamic warping	Call graph visualization & design pattern detection	High runtime overhead
[34]	2025	Transition probability matrix	Malware visualization for imbalanced classification	Limited generalization
[35]	2025	Systematic review	Visualization for financial literacy improvement	Lack of practical implementation

6. COMPARATIVE ANALYSIS OF VISUALIZATION TECHNIQUES

In the above, several categories are discussed for data visualization. Each of the categories is beneficial for comparing their capability for visualization. They have different strength, capability, dimensionality support in the

context of different domains. The mentioned visualization methods address particular objectives where any single technique is universally not good. Traditionally, several visualization techniques such as line chart, bar chart, pie chart, etc. are effective for datasets where dimensionality is low. Two visualization methods, such as choropleth map and scatter chart, provide better relationships in spatial visualization. OLAP cubes extend the function to enable multi-dimensional interactive data exploration. Table 5 illustrates the different characteristics of the visualization methods discussed throughout the survey. Moreover, Table 6 also illustrates the comparative analysis of different attributes of some existing methods.

Table. 5 Comparative analysis of some common graphical methods.

Visualization Method	Dimensionality	Strengths	Weaknesses	Typical Application
Pie Chart	1	Simple depiction; intuitive to most	Not effective for >5 categories; poor for comparison	Part-to-whole relationships
Bar Chart	1-2	Excellent for comparison and ranking	Limited to few variables/trends	Category value comparisons
Line Chart	1-2	Shows trends over intervals of time	Not suitable for non-time data	Time series, trend analysis
Boxplot	1-2	Visualizes distribution and outliers	Only for univariate data	Distributions, variability, outliers
Scatterplot	2-3	Reveals correlations/patterns	Overlap, scaling with large data	Bivariate trends, regression analysis
Choropleth Map	1+ (Spatial)	Geographic patterns	Only for spatial data, prone to misinterpretation	Spatial/geographic distribution
OLAP Cube	3+	Supports aggregation, slicing, dicing	Complex interface; setup required	Multidimensional summaries

Table. 6 Comparative analysis of different attributes of some existing methods.

Ref.	K ₁	K ₂	K ₃	K ₄	K ₅	K ₆	K ₇	K ₈	K ₉
[11]	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No
[12]	Yes	No	Yes	No	Yes	No	Yes	No	No
[13]	No	Yes	Yes	No	Yes	No	Yes	No	No
[14]	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No
[15]	Yes	No	No	No	No	Yes	Yes	No	No
[16]	Yes	No	Yes	No	Yes	No	Yes	No	No
[17]	Yes	No	Yes	No	Yes	No	Yes	No	Yes
[18]	No	Yes	Yes	Yes	Yes	No	Yes	No	Yes
[19]	Yes	No	Yes	No	No	Yes	Yes	No	No
[20]	Yes	No	No	No	No	Yes	Yes	No	No
[21]	Yes	No	No	No	Yes	Yes	Yes	No	No
[22]	No	Yes	Yes	No	Yes	No	Yes	No	No
[23]	No	No	No	No	No	Yes	Yes	Yes	No

Key Attribute: K1: Interactive, K2: Scalability, K3: Multi-Dimensional Data, K4: Real-Time Processing, K5: Automation Level, K6: Interpretability, K7: Visual Clarity, K8: Domain Flexibility, K9: Graphics Processing Unit Support

7. CONCLUSION AND FUTURE WORK

This survey paper effectively reviewed and analysed the four different categories of data visualization, such as projection and dimensionality reduction techniques, interactive visualization and visual analytics, visualization design and rendering techniques and domain-specific application visualization techniques. Each of the techniques supports the complex datasets and helps to generate insightful information based on an effective decision-making system. Although the current cutting-edge areas support different effective tools, challenges like handling high-dimension datasets, scalability, etc. remain unsolvable. The future research direction is to design efficient and adaptive tools that are user-friendly and address the emerging data analysis and visualization.

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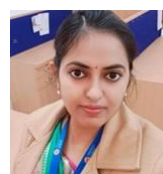
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