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A Systematic Review of 3D Metaphoric Information Visualization

A.S.K. Wijayawardena
IIC University of Technology, Phnom Penh, 121206, the Kingdom of Cambodia
Email: asithask@gmail.com

Ruvan Abeysekera
IIC University of Technology, Phnom Penh, 121206, the Kingdom of Cambodia
Email: ruvan@iic.edu.kh

M.W.P Maduranga
Department of Computer Engineering, General Sir Kotelawala Defence University, Sri Lanka
Email: pasanwellalage@kdu.ac.lk

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Abstract: Today, large volumes of complex data are collected in many application domains such as health, finance and business. However, using traditional data visualization techniques, it is challenging to visualize abstract information to gain valuable insights into complex multidimensional datasets. One major challenge is the higher cognitive load in interpreting information. In this context, 3D metaphor-based information visualization has become a key research area in helping to gain useful insight into abstract data. Therefore, it has become critical to investigate the evolution of 3D metaphors with HCI techniques to minimize the cognitive load on the human brain. However, there are only a few recent reviews can be found for 3D metaphor-based data visualization. Therefore, this paper provides a comprehensive review of multidimensional data visualization by investigating the evolution of 3D metaphoric data visualization and interaction techniques to minimize the cognitive load on the human brain. Complying with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines this paper performs a systematic review of 3D metaphor-based data visualizations. This paper contributes to advancing the present state of knowledge in 3D metaphoric data visualization by critically analyzing the evolution of interactive 3D metaphors for information visualization. Further, this review identifies six main 3D metaphor categories and ten cognitive load minimizing techniques used in modern data visualization. In addition, this paper contributes three taxonomies by synthesizing the literature with a critical review of the strengths and weaknesses of metaphors. Finally, the paper discusses potential exploration paths for future research improvements.

Index Terms: 3D Metaphors, Interactive Data Visualization, Human-Computer-Interaction, Metaphoric Data Visualization

1. Introduction

Technological advancements and numerous human requirements have led to more complex data collection in many application domains such as health [1], finance [2] and business [3] as well as information technology systems [4]. In addition, there is a rapid growth of data consumption by users over the internet in their daily activities. However, using traditional data visualization techniques, it is challenging to visualize abstract information to gain valuable insights into complex multidimensional datasets. One major challenge is the higher cognitive load in interpreting information as it requires more brain power in interpreting a complex dataset. One reason for this is, that the natural setup of the human brain has limited processing capacity. However, the human brain can process pre-attentive visual properties of a visible figure within several milliseconds [2,3]. Therefore, visualization of information using graphical forms works better than text data in understanding and making effective decisions on datasets [7]. In this context, 2D and 3D data visualizations are used in getting valuable insights into datasets via transferring the cognitive load into the visual cortex of the human brain. However, with traditional 2D data visualization approaches, users have to keep the mapping relationships between data variables and attributes of visual representation in their minds to get valuable insights into datasets. Therefore, it is difficult to remember the mapping relationships with many variables [8] in complex datasets. Thus, 3D metaphor-based information visualization concept has emerged as a novel area of research under visual data analytics which tends to transfer correlated attributes from familiar objects to understand unfamiliar concepts [9]. Furthermore, 3D metaphors can bring more intuitive data visualizations with familiar ideas to the user and higher user engagement [10].

Several metaphor-based works have been reported in the literature to visualize data of different application areas like software visualization [11], financial data visualization [2], social media data visualization [12], etc. However, there are a limited number of publications to get a comprehensive understanding of the existing 3D metaphoric data visualizations. Because of that, there is a requirement in the literature to discuss the limitations, trends and their different application scenarios etc. on existing 3D metaphoric data visualization techniques. Therefore, this paper attempts to review several recent works on 3D metaphorical data exploration together with their pros and cons while examining potential paths for future research improvements. As described below, the PRISMA guidelines [13] have been adapted to organize the review in a systematic way. Critically reviewing the literature, this paper contributes three taxonomies by summarizing the related work in the past. Moreover, this paper attempts to address the following question in a systematic manner.

RQ: How 3D metaphors have evolved with HCI techniques to minimize the cognitive load on the human brain?

The rest of this paper is organized as follows to investigate this topic. In the first section, there is a review of currently available 3D metaphors for information visualization. Secondly, it discusses types of 3D metaphors followed by a taxonomy. Different approaches to human-computer interaction used in the metaphors are discussed and summarized into a taxonomy in section three. The fourth section provides a discussion outlining the different types of 3D metaphors. The final section concludes the paper with findings and an outlook on potential exploration paths for future research improvements.

2. State-of-the-art in information visualization

In contrast to early-day information visualizations, advanced computer graphic techniques are being used and investigated for the visual exploration of complex datasets. The concept of metaphors plays a key role in today's data visualization. Aligning with the objectives of the paper, this section attempts to highlight some of the growing body of recent research that involve several 3D metaphoric concepts which demarcate the current state of information visualization. Further, it would be helping for researchers to grasp the current state of metaphors and how they are utilized in application domains. Literature reports that information visualization involves the graphical representation of different aspects of data through visual elements such as charts, maps, and graphs. The typical reason is that human sense-making highly depends on vision [14]. Therefore, it is argued that 3D visualization helps to reduce the brain's cognitive load in performing analytical tasks [15]. As a result, a growing body of research has proposed different metaphors for modern data visualization under different application areas. The following paragraphs discuss several recent metaphoric concepts under research in different application domains.

City metaphor has become one of the most frequently used real-world metaphoric concepts for software visualization. A real-world city can be organized into three hierarchical levels city, districts and buildings. In their work, N. Capece et al. [16] suggest a city metaphor-based visualization for object-oriented software systems written in Java. Software systems are visualized as real cities, and the classes are represented as buildings while the packages are presented as districts. In recent literature, several other works reported using the city metaphor to visualize data related to software production [13,14,15]. Therefore, the city metaphor has become highly demanding in visualizing complex software system data. However, in contrast to software visualization, the City metaphor has been adapted to visualize data in different contexts. For instance, M. Weninger et al. have adapted the city metaphor and proposed Memory Cities to visualize the evolution of heap memory over time [20]. Applying a similar concept by Weninger et al. [21], the City metaphor has been utilized to visualize the dynamic behaviour of memory evolution of the applications over time. Heap objects have been grouped according to arbitrary properties such as allocating thread or type of heap object. The objects are then represented as buildings where the number of objects resembles the size of the building. In very recent work, R. Sicat et al. [22] propose Cloud Cost City metaphor to visualize cloud infrastructure architecture and the associated costs. Buyuksalih et al. [23] present a 3D City modelling to visualize data in managing big cities to assist urban development planning.

Another different metaphoric approach has been attempted by A. Schreiber et al. [15] to visualize module-based software systems. Using a dynamic graph algorithm, the islands of the archipelago are positioned to give a better overview. The proposed metaphor is called Island Metaphor which is based on the concept of a real-world island system on a water surface. The regions of the islands provide room to reside in all of the buildings without overlapping each other. Therefore, the island size depends on the number of class types inside a package. This approach allows users to understand the complexity of the intended software system and interactively explore the modules and dependencies. However, this visualization is specially designed to enhance the understanding of complex software architectures.

Apart from the city metaphor, D. Atzberger et al. [24] proposed Software Forest based on the Tree Metaphor. Software Forest maps different software properties such as trend data and size metrics to visualize various aspects of software systems as a forest. In addition to these metaphors, the universe metaphor [25], terrestrial metaphor [25], and room metaphor [26] have been proposed by several works to visualize different datasets associated with software systems. According to the literature, these metaphoric visualizations are specially designed to enhance the understanding of complex software systems and they have not been tested for datasets other than software development. Therefore, there is room for further research on other domains.

Metaphoric glyphs are used as another way of improving the intuitive understandability and learnability of data visualizations. Glyphs can encode information using small graphical signs' shape, colour, size, and arrangement [27]. In their work D. Presnov et al. [28] propose a technique of constructing metaphoric glyphs over abstract glyphs to visualize quantitative multidimensional data. These glyphs are built upon intuitively related graphical entities of the underlying domain. Presentation settings of the metaphoric glyphs can be based on the layout and the number of glyphs in the view. A growing number of works have been reported in the literature for several designs of data glyphs across many different disciplines. For instance, D. Rees et al. [29] attempt to visualize the agent behaviour of call centres by utilizing multivariate glyphs in a scatterplot layout. Another glyph-based work proposes a visualization called Glyphboard [30], a zoomable user interface using the dimension reduction method. Therefore, the users can quickly spot the relevant dimensions of the data set at a glance. However, this work currently does not allow the users to edit data but focuses on the observation level interactions using a mouse and keyboard. An overview of glyph-related visualizations and a survey are presented by J. Fuchs et al. [31]. Furthermore, the paper discusses design implications and open research directions based on the meta-analysis. Moreover, some works have been reported in the literature to improve the development environments for glyph-based data visualizations in 3D. For instance, R Sicat et al. [32] present a glyph-based data visualization toolkit to support the implementations of 3D data visualizations. The toolkit promotes 3D visualizations to embedded data representations while providing reusable templates and customizable graphical marks. However, overlapping issue is common and challenging when compared with other metaphoric data visualizations. Therefore, glyph placement algorithms need to be fine-tuned to address this problem. Further, modern interaction techniques can be incorporated to make them much more realistic.

Recent literature reports several other metaphors used in different contexts. For example, VirtualDesk [33] is another alternative 3D metaphor for data exploration. VirtualDesk allows the users to interact using natural mid-air gestures and manipulates the data render at arm's reach. In another work reported in the recent literature, a Space-Time Cube [34] has been used over a trajectory dataset in geo-visualization. Coupling the Space-Time Cube with the VirtualDesk metaphor has formed an immersive desktop-based implementation. According to the evaluation results, it has received higher usability scores and user preference while reducing the mental workload. A review of the Space-Time Cube has been presented by Bach et al. in their paper [35].

Very recently, a hybrid visualization called Tilt Map [36] has been proposed by Y. Yang et al. to explore area-linked data. Tilt Map involves Choropleth Map, Prism Map, and Bar Chart where tilting allows users to engage with natural interactions. Utilizing terrain metaphor [37], Y. Zhang et al. have proposed another metaphoric approach to visualize the relationship among the data points of attributed graphs. Another work by L. Sancho-Chavarría and E. Mata-Montero [38] suggested an interactive web-based 3D environment involving cone tree metaphors to visualize hierarchical data related to biological taxonomies. In addition to the visualization capability, an editing functionality was introduced to create and maintain taxonomies. Finally, in contrast to traditional visualizations, Latvala et al. [39] propose a 3D fish tank metaphor to explore network events of industrial automation systems. In connection with a natural fish tank concept, the network nodes are represented using different kinds of fish while their movements describe the respective events.

Theoretically, it can be considered that all the visualizations are metaphoric. However, there are traditional metaphors that are much more familiar to the user than newly proposed metaphors. In this context, Averbukh [40] presents a semiotics analysis of computer metaphors important in designing visualizations. Further, it allows the search for new metaphors and evaluates known metaphors. In general, not all metaphors are suitable for all possible data visualization scenarios or cases. Therefore, it is still a challenge to select and design intuitive metaphoric representations for all the complex datasets.

3. Methodology

Systematic reviews should follow predefined structured methods to classify, evaluate and synthesize the appropriate literature to maintain quality. Therefore, this review adapts the steps and guidelines given in PRISMA 2020 [13] to review publications systematically. Fig. 1 depicts the four-phase flow diagram of PRISMA. A protocol was prepared with the following elements in line with PRISMA guidelines. (i) Research question, (ii) Information source (iii) Search of publications, (iv) Study selection, (v) data extraction and meta-analysis.

3.1. Research question

A research question is crucial to define and set clear boundaries for a systematic review. Therefore, this review is inspired by the research question stated in the introduction section. Additionally, it helps to foresee potential problems or challenges for further investigations.

3.2. Information source

Search in Google Scholar with keywords and selected publications from reputed journals and conferences within the last decade from 2011 to 2021.

3.3. Search of publications

A systematic electronic search was performed on Google Scholar to identify all studies that comply with eligibility criteria. Mainly, searching required publications were based on the keywords for 3D metaphoric data visualizations. The duration parameter of the search was set to capture publications within the last decade. However, few papers were selected out of this range to monitor the evolution. Some general terms such as data visualization 2D metaphors were excluded during the pilot search and focused on 3D metaphoric data visualization approaches. With the results of the pilot search, it was decided on the exclusion and inclusion criteria. The search strings were mainly centred around 3D metaphoric data visualization. It is to capture all possible 3D metaphoric data visualization approaches. The following are the inclusion and exclusion criteria incorporated in this review.

Inclusion Criteria

- Full papers published in interactive 3D metaphoric data visualization
- Same metaphor in different contexts

Exclusion Criteria

- Papers with fewer contents
- Leaflets, posters, website, technical report, workshop reports
- Duplicate papers
- 2D and 2.5D metaphors
- Having citations count below 10

3.4. Study selection

After searching the papers, a manual inspection was carried out to check whether the study was relevant to the intended purpose of the review. For instance, even if a particular paper discusses 3D metaphors, it may not be in a data exploration context. Furthermore, non-interactive 2D or 3D metaphors were excluded. Therefore, only the interactive 3D metaphors related to data visualizations were selected according to the scope of this review. In addition, papers with very few pages, such as 2 or 3, were banned and maximized by including reputed and recently published journal and conference papers within the last ten years. According to this screening process, twenty-nine unique metaphors were identified out of sixty publications (Table 02).

3.5. Data extraction and meta-analysis

Reading the selected papers, essential facts about 3D metaphors such as the metaphoric concept applied, cognitive load minimizing techniques, types of interactions, datasets, etc., were captured. These facts were used in the critical analysis of each 3D metaphor. The findings of the selected studies and characteristics are systematically presented using relevant figures. Therefore, taxonomies and tables have been prepared based on the collected data, and the outcome of the meta-analysis is presented using statistical methods.

According to the protocol described above, this paper systematically reviews the 3D metaphoric information visualization in subsequent sections. The following Fig. 1 shows the information flow through the different phases of the review.

3.6. PRISMA flow diagram

The below flow diagram (Fig.1) visually depicts the process of finding published data on the topic of this paper. The decision to include a particular paper in this review was decided based on it. This diagram consists of four main stages of the systematic review as described in the following subsections.

3.6.1 Identification

Identification of the articles is crucial in a review. Therefore, as the first step papers were searched through Google Scholar. Additional records were identified through citation databases. All the search records from databases and other sources were combined and put into one citation management program (Zotero). Using the article’s digital object identifier (DOI), duplicate records were searched and removed from the collection.

3.6.2 Screening the articles

The second level of the PRISMA diagram depicts the screening of articles. It involves reading of title and abstract of each record to determine whether the article contains relevant or supportive materials for the systematic review. However, the excluded review articles would contain references to useful research studies that were not returned in the original searches. In that case, those are considered additional records under stage 01 of the diagram.

3.6.3 Deciding on the eligibility

In the third step, the remaining articles of the second stage determine whether the articles are supportive to answer the research question. All of the articles were fully read and decides whether to include or not to include the studies in the qualitative synthesis.

3.6.4 Finalizing the list of studies to include in the systematic review

The number of studies included in the systematic review is determined by excluding irrelevant studies in level -03. Therefore, it can be identified and counted the number of studies that can be included in the quantitative synthesis (meta-analysis). However, all eligible studies for the systematic review may not be eligible for the quantitative synthesis. This is because all the studies may not contain the data necessary for the meta-analysis (below section 4).

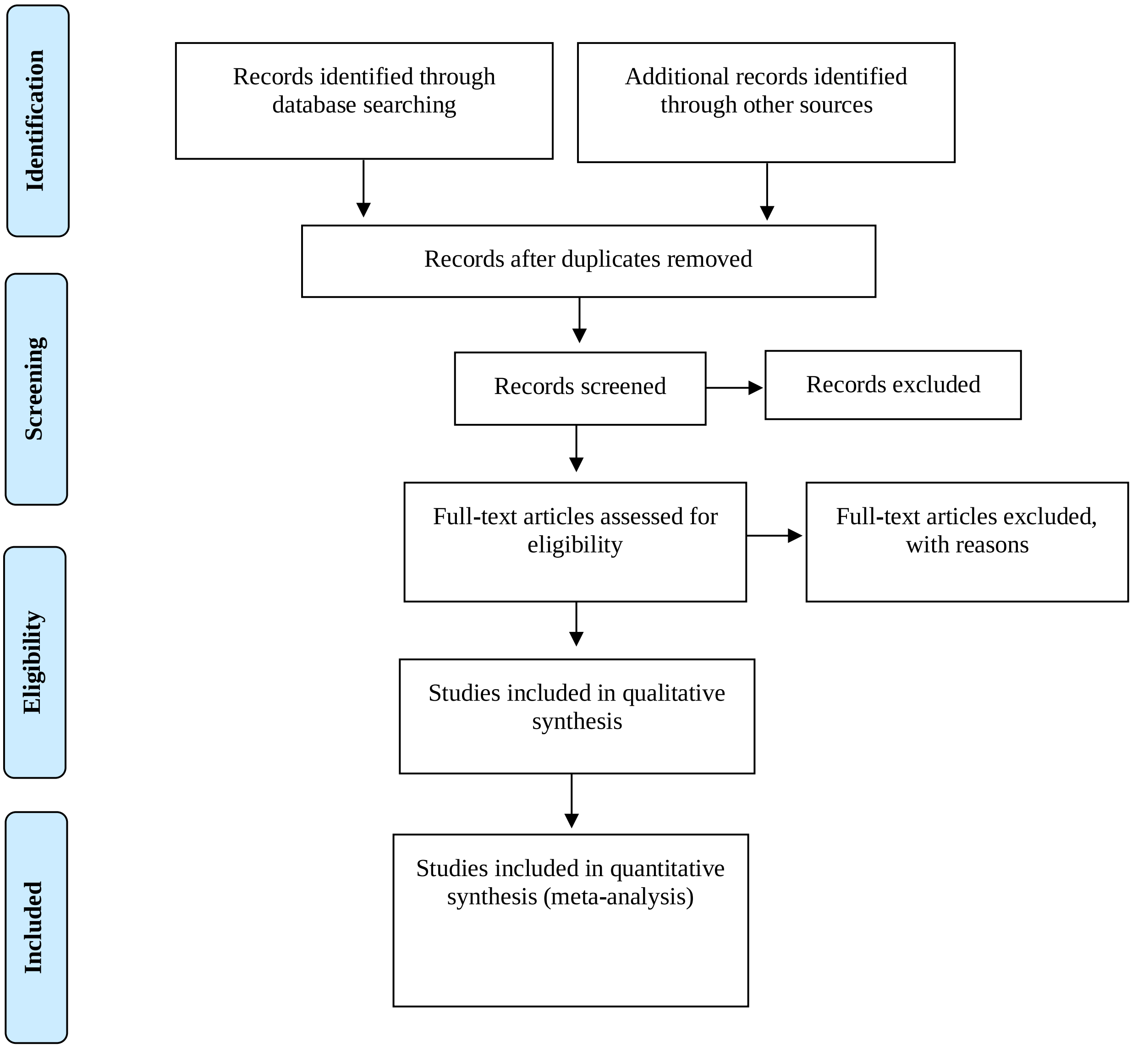

Fig. 1. Four-phase flow diagram of PRISMA

4. Types of 3D Metaphors and their Interactions in Data Visualization

Information communication is mainly driven by the underlying mechanisms of metaphors. Therefore, metaphors are pervasive in information visualization. According to the literature, several attempts have been made to visualize complex datasets using 3D metaphors. These different types of metaphors help the data analysts to get many different insights into the datasets. However, there are two main types of metaphors available in the literature. They can be named elementary or primary metaphors and composite metaphors. Following Fig. 2 depicts a taxonomy of mostly used types of metaphors for information visualization in 3D. However, there can be many extended versions of metaphors to those main types of metaphors. A summarization of metaphors is available in Table 02.

4.1. Composite Metaphors

Literature reveals that several works have been carried out to propose different composite metaphors built by composing several elementary metaphors. For instance, the Software Forest [24] metaphor uses elemental metaphors such as trees and islands. The City [11] metaphor may use buildings and several landmarks as elementary metaphors. It makes a multimodal virtual environment that incorporates several elemental metaphors. Moreover, these composite metaphors are used to create game-like 3D interactive environments and 3D user interfaces to implement more intuitive visual data exploration [41].

4.1.1. Metaphoric worlds

Metaphoric worlds are one of the main categories of 3D metaphor-based information visualization. It utilizes familiar hierarchical environmental concepts to make it easy to understand information. These metaphors combine components such as 3D glyphs in a hierarchical arrangement while allowing users to interact and navigate. Visual parameters are used in each graphical element to visualize useful information. According to the literature, metaphoric worlds can also be divided into three subtypes depicted in Fig. 2. These metaphorical types fall into cosmos, physical constructions, and geometric metaphors.

Different visualization techniques have been proposed based on the various special encodings. Cosmos metaphors involve the concepts associated with the cosmos. The solar system metaphor [12] is a typical example of a cosmos metaphor with the composition of planets, glyphs, moons, stars, and satellites. These metaphors involve the intuition of natural phenomena in visualizing and interacting with the metaphoric world. Galaxy is another metaphor of cosmos metaphor. They mainly focus on the spiral perspective and behaviour of a galaxy described by astronomers. In their work, Happa et al. [42] have used this galaxy concept to detect anomalies in the context of cyber security. Further, the cosmos metaphors naturally offer nested arrangements of orbits via multidimensional physical variables allowing us to understand the relationships in the datasets [12].

Physical perspective and the notion of the environment of human-made objects have been used in creating these types of metaphors. For instance, the room metaphor [43] represents the environment of a room, and buildings [44] can represent the outside environment of a room. This type of metaphor generally captures the three-dimensional geometry of a building together with its structural properties.

Geographic metaphors use the concept of terrain in a geographic area. For instance, landscape and city metaphors represent terrain views in visualizing linked datasets in multidimensional information environments [11]. This type of metaphor has become famous in the context of software visualization. There are many works reported in the literature on this category for visualizations of different attributes of software production [11,12,13,16] among software development teams for better comprehension of the process. Utilizing multiple trees Hansch and Hellwich [45] have proposed a Random Forest metaphor with a set of decision trees to visualize high-dimensional data. It offers higher accuracy and learnability in visualizing higher dimensional data [46].

4.1.2. Geometrical Metaphors

Another subtype of composite metaphors is geographic metaphors. These metaphors involve objects with geometric shapes and associated features. For instance, parallel coordinates [42,43,44] and cube-based metaphors like matrix cube [50] assemble objects in a geometrical shape of a cube. Another type of geometrical metaphor is the spherical metaphor [46,47]. However, geometrical metaphors are primarily used in visualizing multivariate and multidimensional datasets.

4.1.3. Compound Objects

Compound objects can be made out by combining several other associated objects. For example, Latvala et al. [39] present a fish tanks metaphor to visualize network data. The fish tank metaphor is a single object composed of many other small objects like fish, water plants, and other things involving aesthetics. In this 3D fish tank, network nodes are represented using different kinds of fish. Further, the network events are visualized by the movements of fish.

4.2. 3D Glyphs as metaphors

Metaphoric glyphs are another way to present multidimensional data through their visual channels. In glyph-based metaphors, the dataset is visualized as a collection of small graphical objects. Collectively, it is referred to as a glyph. There are many applications available in the 2D context. However, it is still challenging to visualize complex multidimensional data using 3D glyphs. Compared to 2D, the additional dimension allows visualizing more information. Occlusion is one of the challenges for glyph-based metaphoric approaches. Therefore, the glyphs are frequently placed on 2D surfaces such as feature surfaces or slicing planes to overcome occlusion. Further, it would result in visual clutter and occlusion when more glyphs are placed in the 3D space. However, there are some attempts have been made to overcome such barriers. For instance, Tong et al. propose GlyphLens [53], allowing data analysts to pick a glyph and analyze it from different perspectives. Glyphs-based visualizations allow the perception of patterns of multidimensional attributes of unique relationships readily. In their paper, Borgo et al. [54] review glyph-based visualization while reviewing the design guidelines and implementation techniques. However, designing compact glyphs for data representation is challenging in glyph-based metaphors [55].

4.3. Structural Metaphors

Information structuring is an essential application area of information visualization. The selection of quantifiable attributes of a data domain can be made easy by incorporating effective information structuring. This type of metaphor involves a particular 3D visual structure representing information such as 3D Matrix [56], and 3D Cone-Tree. In general, most hierarchical structures provide intuitive as well as compelling visualizations for hierarchical data. For instance, 3D cone trees visualize and interact with hierarchical data in 3D information space [57]. Visualizing structured relational information as hierarchies is very common. In this context, hierarchical metaphors play a vital role in visualizing complex datasets. Mainly hierarchical metaphors are used to visualize graphs that involve node-link representations. These metaphors are common in data visualization areas such as Social network analysis [58], network information [59], and software visualization. However, 3D node-link visualizations result in complicated edges and nodes when the number of connections increases. As a result, it may create a confusing figure which is difficult to interpret [60]. In their paper, Chen et al. [61] present a survey on graph-based structural visualization in the context of exploring the relationships in complex datasets. Apart from visual representations, some structures have been used to create more intuitive interactive visualizations. For example, the 3D carousel metaphor has been used for setup a cyclical arrangements in interactive data visualizations [57,58].

4.4. Natural Phenomena as Metaphors

According to literature, some works propose natural phenomena as metaphors. For instance, Würfel et al. [64] visualize software metric trends on a static trend map using natural phenomena like rain, fire, and material properties such as rust, shininess and glow. This type of metaphor has been used to express situational awareness of ongoing processes dynamically. For instance, however, it is challenging to identify suitable natural phenomena to communicate trend data effectively [40].

4.5. Biological Metaphors

Biological metaphors are used to visualize information with familiar concepts in biology. These concepts can be a structure of interconnected neurons or nerve cells [65]. For instance, Mindek et al. [66] propose a metaphor as a biological neural network to visualize graph structures. Another example would be the Neurolines [65], which allows visual queries on larger data sets having neurite connections.

4.6. Botanical Metaphors

According to the literature, some metaphoric concepts are closely associated with realistic models of plants in nature. Therefore, it brings another type of 3D metaphor identified as botanical metaphors. Mostly used metaphor under this category is the botanical tree. Data are visualized as a tree arrangement having branches and leaves. For example, Kleiberg et al. [67] proposed a botanical tree-based visualization for larger hierarchical data structures. In general, botanical visualizations have been used to present the associations among trees, branches, and fruits in a 3D context.

4.7. Other Metaphors

There are metaphors made out of other metaphors that are impossible to group under the categories mentioned above. For instance, the Book metaphor [68] visualizes XML data related to vacation packages. This type of metaphor is categorized into other metaphors. However, these metaphors are very rarely used in the literature for information visualization.

4.8. *Taxonomy of 3D Metaphors*

Based on the above discussed 3D metaphors are summarized in the following taxonomy in Fig 2. As the main interest of this study is to review the evolution of 3D metaphoric data visualization, the root (level-0) of the taxonomy has become 3D metaphors for data visualization. Level 01 of the taxonomy represents seven major categories of 3D metaphoric concepts that can be recognized while analyzing the literature. These main types are further decomposed in the subsequent levels (level 02 and level 03). Finally, the leaf nodes of the taxonomy represent the typical examples that implement those metaphoric concepts. Each of these types is described in the above sections. Further, following Table 2. Summarizes the types of 3D metaphors with dataset types, Human-Computer Interaction Techniques and exemplary work of these metaphors.

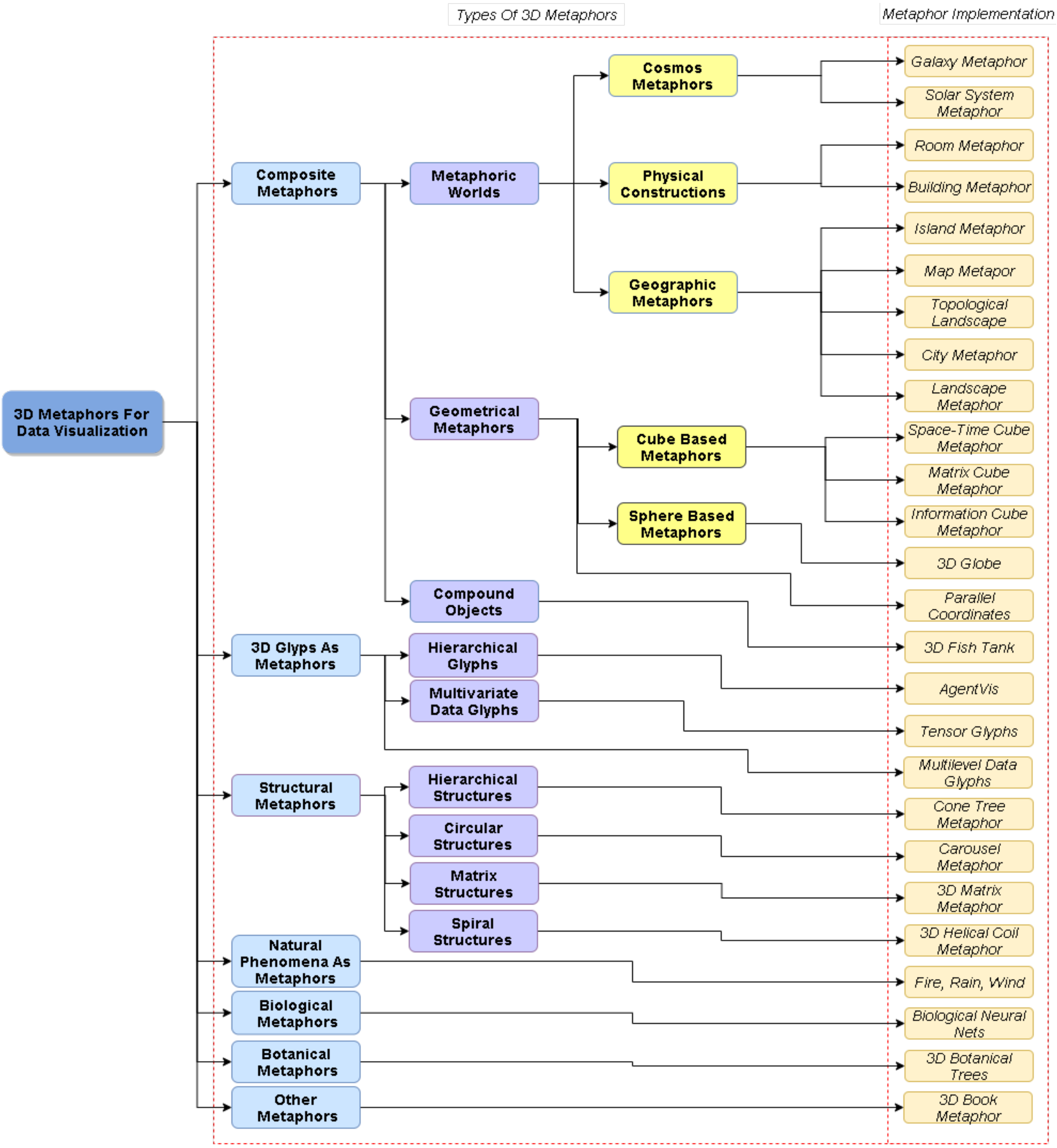

Fig. 2. Taxonomy of 3D metaphors

4.9. Quantitative synthesis (Meta-Analysis)

As per the publication selection (60 publications), it could be identified six major categories of 3D metaphors as depicted in Fig. 3. According to the number of publications, the distribution of these categories is depicted in the following Fig. 3. Considering the number of publications, composite metaphors are dominating in 3D metaphoric data visualization.

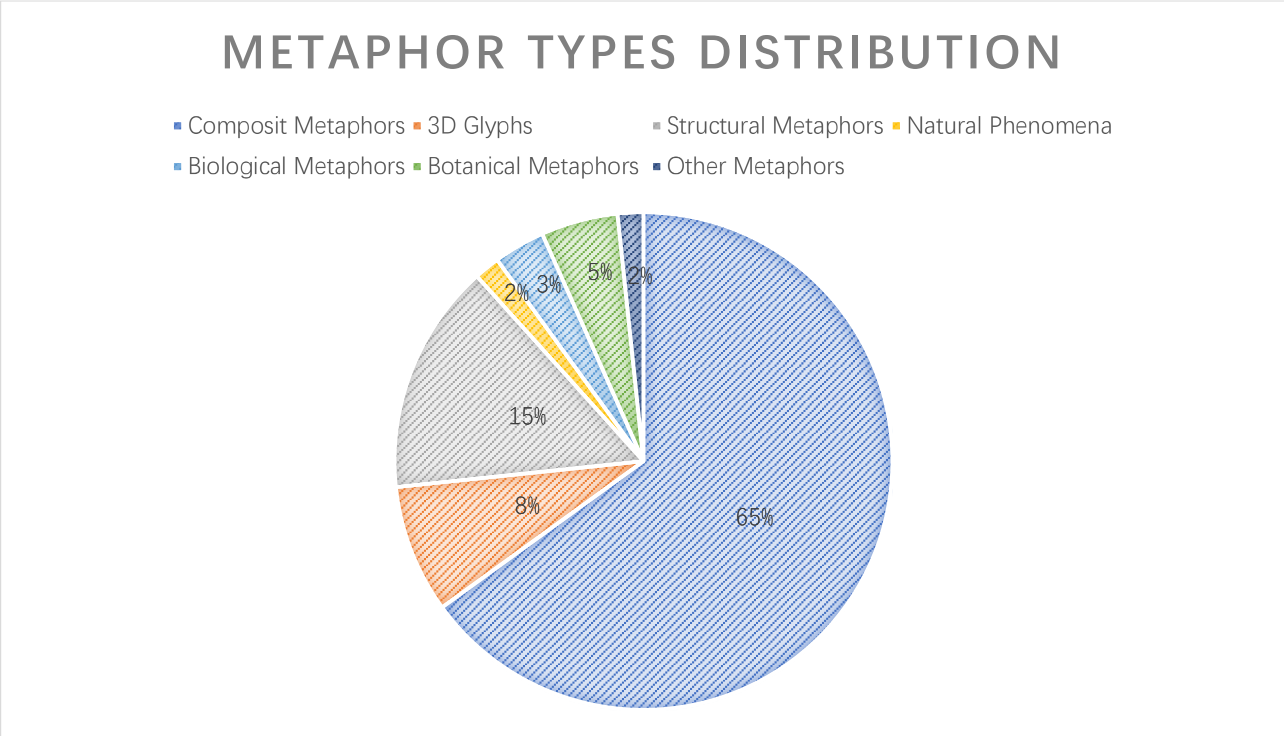

Fig. 3. 3D Metaphor Types in Data Visualization

However, the primary metaphor categories can be further broken down. According to the number of publications selected for the analysis of this review, the distribution of the individual metaphors is depicted in Fig. 4. According to Fig. 4, metaphoric worlds have the highest demand. One reason for this would be many of the cognitive load minimizing techniques based on virtual reality are applied in metaphoric worlds (Table 01).

4.10. Interactions

Lakoff and Johnson [69] stated primary metaphors ascend from experience gained through the human lived. In this context, interaction techniques play an essential role in creating intuitive interfaces under metaphoric information visualizations in 3D. The advancement of devices has made it possible to create realistic interactions closer to real-world interactions over conventional mouse and keyboard interactions. However, interaction occurs via various methods such as eye gaze, hand, and walking [70].

Several works have investigated novel ways of interacting in the context of metaphoric information visualization in 3D. For example, Sidorakis et al. [71] propose a gaze-controlled multimedia user interface for modern immersive headsets. This work is based on the binocular eye-tracking of the user, and it has been implemented in several multimedia applications. Utilizing the eye gaze pattern, it can perform eye-based typing of E-Mails using a virtual keyboard. In their paper, Kar et al. [72] present a detailed review of the recent advances in eye-gaze interactions. According to the literature, there exist some multimodal implementations combining several interactions. For instance, Han and Kim [73] propose a gaze-based hand interaction to overcome the limitations in touch inputs for mobile devices when the mobile device is required to be attached inside the Head Mounted Device (HMD) where touch inputs are not possible. Both hand gestures and eye-gaze are used to implement the interaction. Another work by Srinivasan and Stasko [74] presents a multimodal interface involving touch-based direct manipulation and natural language input for network visualization. Fig. 5 presents a taxonomy of human-computer interactions used in modern 3D metaphoric visualizations.

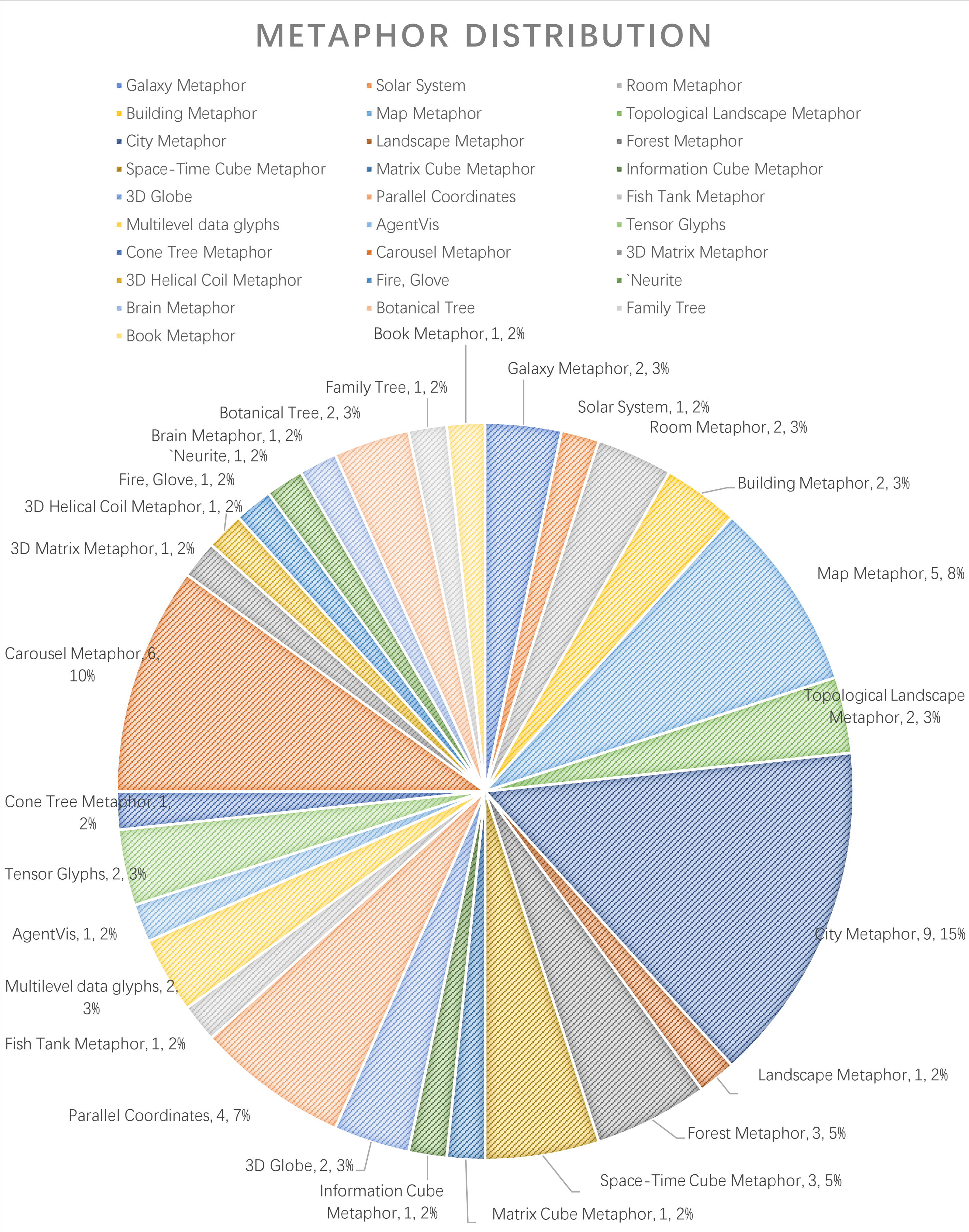

Fig. 4. Distribution of metaphors according to the number of publications selected for the analysis

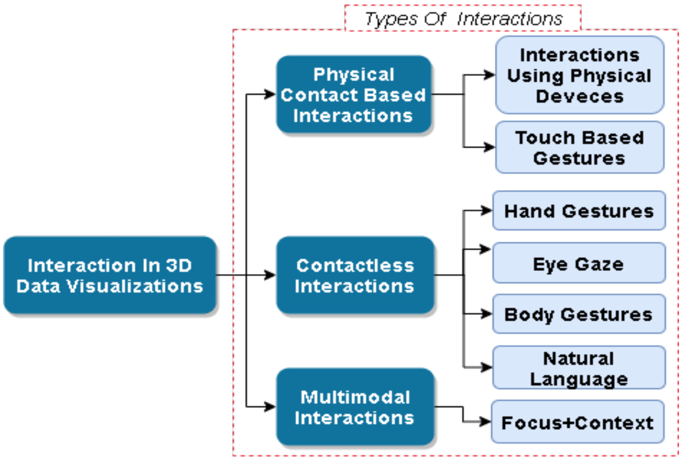

Fig. 5. Taxonomy of human computer interactions

5. Discussion

According to the Meta-Analysis, it could be found that it is still challenging to minimize cognitive load in interpreting modern complex datasets. To address this problem 3D metaphoric data visualization approach has evolved with HCI techniques. Therefore, metaphors are used in different contexts for visualizing different natures of data. According to the psychology of metaphors, a good metaphor should provide the realistic mapping of a familiar domain with an unfamiliar domain in terms of relationships and elements [69]. However, different connotations can be found in different domains. For instance, the software is visualized using the city metaphor [6,12] where those are in two separate domains and software is intangible. Because of this, it is defying to prepare taxonomy on 3D metaphor with present data visualizations. Moreover, the same metaphor may belong to two types depending on the different contexts. For example, both the city and solar systems have a hierarchical aspect by nature. City metaphor composites components such as districts that contain streets and buildings. Then the buildings contain floors and floors contain rooms and so on. Similarly, the Solar system includes planets, then contains moons, etc. Therefore both metaphors have been used in the context of software visualization [8,12,13]. However, this paper attempts to categorize only the 3D metaphors in the context of data visualization in 3D. Table 02 summarizes the different types of 3D metaphors with their visualizing datatypes, human-computer interactions, and exemplary work. According to the analysis results of this review, it could be observed that there are many techniques have been applied to minimize the cognitive load on the human brain in visual data analytics. As depicted in Fig. 6, these techniques could be broadly divided into two major categories as metaphoric designs and interaction techniques. The following sections discuss the strengths and weaknesses of 3D metaphor types followed by metaphoric approaches to minimize the cognitive load on the human brain and future directions with open research areas. Finally, Table 1 summarizes cognitive load minimizing techniques used in different types of metaphors.

5.1. Strengths & Weaknesses

One of the main benefits of metaphoric worlds is bringing familiar environments to the user when analyzing datasets. Metaphoric worlds represent data using naturally available concepts such as Solar Systems [12], Cities [12,13,14,16], Islands [15], Landscapes [75], Rooms [26]. It helps to minimize cognitive load in visual data analytics. For instance, researchers have attempted to visualize software differently through instantiating city metaphors by leveraging physical cities and software analogy.

When there are many dimensions in the visualization, it leads to over-plotting and overlapping in traditional visualizations. As a result, it results in difficulty in interpreting the dataset. Metaphoric worlds efficiently utilize the 3D space to visualize additional dimensions. Another main benefit of metaphoric worlds is using 3D graphical concepts similar to real-world entities. It enables the representation of data more naturally. As a technique to minimize cognitive load, the metaphoric worlds represent data using naturally available concepts such as Solar Systems [12], Cities [12,13,14,16], Islands [15], Landscapes [75], and Rooms [26]. It helps to minimize cognitive load in visual data analytics. For instance, researchers have attempted to visualize software differently through instantiating city metaphors by leveraging physical cities and software analogy. With the aid of virtual reality, users may immerse in the metaphoric worlds. In addition to the 2D interactions using a mouse and keyboard, metaphoric worlds incorporate many Human-Computer interaction techniques such as natural user interfaces with direct manipulation [11,22] to empower cognitive efficiency (Table-02). Nevertheless, it remains a challenge to visualize more than three dimensions. In contrast to other types of metaphors (Fig.1), metaphoric worlds have more potential of visualizing complex, higher-dimensional and dynamic datasets, such as big-data [8,70], and financial [2] data. Moreover, such data's volume, variety, and velocity require more sophisticated visualization due to the information's speed, size, and diversity. Therefore, designing a novel interactive 3D metaphoric world has become a challenge.

5.1.1. Geometrical Metaphors

As listed in Table 02, the geometric metaphors visualize various datasets, including multivariate, multidimensional, and hierarchical datasets. However, the visualizations are limited to primitive geometrical shapes and their visual properties such as height, width, volume, etc. Therefore, it is challenging to visualize slight differences in the datasets using such optical properties. Further, the number of objects in the 3D space is another way to visualize information using geometric metaphors. For instance, 3D parallel coordinates use geometric shapes as axes and links to represent the different dimensions having relationships in the datasets [42,43,71]. The data are visualized using columns for each dimension and links connecting them. When the number of dimensions becomes significantly higher, it becomes difficult to interpret, particularly for non-technical people. Only the relationships between adjacent axes can be understood easily. However, relationships between nonadjacent axes are difficult to understand. Geometric cube-based metaphors are very commonly used in visualizing spatio-temporal datasets. However, the general usability is impacted due to 3D navigation, steep learning curve and lack of depth cues. Furthermore, it is reported that occlusion and distortion are other shortcomings of geometrical metaphors. Sphere-based 3D metaphors are also commonly used in data visualization. Sphere-oriented visualizations are standard, especially for geographic data visualizations [46,47,72]. One reason for it would be that the sphere-based metaphors provide an easy way of interacting by rotating. However, the main disadvantage of sphere-based visualizations is that the sphere's curved surface causes foreshortening with distortion and occlusion. Further, only half of the data visualized can be seen at once.

According to the literature, some 3D metaphors are formed as a composition of several other objects. This type of metaphor is currently used to visualize complex datasets and their dynamic behaviours in 3D space [39]. These compounding objects have a natural propensity to a group. For example, typical work has been carried out by Latvala et al. to visualize network events using a 3D fish tank metaphor. Due to the dynamic nature of this metaphor, it can be thought of as storytelling on data to convey information for situational awareness. This type of metaphor combines artistic and esthetics to improve cognitive capacity so that a large amount of information can be easily understood and memorable.

5.1.2. 3D Glyphs

3D glyphs are another powerful way of representing complex multivariate datasets. They can simultaneously present multiple variables of a dataset on a single image. Data glyphs are strong enough to visualize high information density. Further, glyphs can visualize data relations by using custom notations. However, for glyphs to become useful, the design has to be done carefully. Therefore, to design an effective visualization, the visual properties have to be well chosen and combined into the glyphs. Glyphs usually do not stay alone as a single metaphor. They are replicated to form a group and distributed within the visualization. This introduces several problems such as orientation in 3D space, occlusion, complex navigation, and perspective distortion. Therefore glyph placement is very significant, and it requires sophisticated algorithms to place glyphs in 3D space [78]. As listed in Table 02, glyphs are mainly associated with 2D interactions with the mouse, keyboard, etc.

5.1.3. Structural Metaphors

Structural metaphors are very useful to visualize the structure of the vast information space to get better insights into data. One of the main competencies of structural metaphors is maximizing the effective use of screen space available. Furthermore, due to the 3D nature, structural metaphors naturally contain more information and relationships within the dataset. Additionally, these metaphors better exploit the capacities of the perceptual system of humans. For instance, a 3D cone tree diagram can visualize hierarchical information with nodes [38]. These nodes have large multiples, and interactions allow for rotating and observing every child or node in the hierarchy. However, these interactions mainly depend on 2D (Table 02). Therefore, adding 3D interactions can make them more pleasant in engaging visual data analytics.

5.1.4. Natural Phenomena as Metaphors

These metaphors can visualize the dynamic changes of a dataset in 2D space. They effectively visualize data changes by incorporating real-time rendering techniques and additional visual variables. Currently, these metaphors have been attempted to visualize changes over multiple revisions of complex software systems. One shortcoming of this metaphor is that it cannot stay alone. They involve another metaphor to form the visualization. However, they are helpful to augment the cognitive and perceptual capacity in existing complex data visualizations [79]. Furthermore, these metaphors can communicate a dynamic dataset's positive divergence (glow, shine) and negative divergence (incorporating fire, rust, or roughness). For instance, Würfel et al. [64] use the natural phenomena of fire as a metaphor to improve the interpretability of trend data in interactive software maps.

5.1.5. Biological Metaphors

Biological metaphors involve biological concepts to form data visualizations. Therefore, these metaphors are primarily suitable for biology-related audiences who can easily understand them. For instance, Weifeng et al. [80] incorporate a 3D brain metaphor to visualize brain network-related information., In addition to the biological domain, in their work, Huang et al. [81] have proposed a 3D brain graph metaphor to visualize graphs in a stereoscopic 3D space. However, these metaphors are still more towards visualizing scientific data in biological domains.

5.1.6. *Botanical Metaphors*

Botanical metaphors involve natural plants and related objects as metaphors to visualize data. One strength of biological metaphors is to arrange knowledge compactly using a wide variety of trees and plants. Parts of the trees represent the relationships. For instance, Kleiberg et al. [67] have proposed a 3D botanical tree metaphor to visualize large hierarchical data structures. The information is abstracted by the arrangement of the trunk, branches, leaves, etc. Therefore, these metaphors help get an overall abstract idea of a dataset. Currently, these metaphors try to address the functional difficulty of tree diagrams when they become complex with larger datasets. Even with more branches and leaves in real trees, they usually maintain distinct visual entities. Therefore, the concept of tree diagrams has been extended by introducing the branches and leaves of a natural plant. However, 3D botanical metaphors are still limited to hierarchical data structures. Further, the data analysts would require some knowledge of the dataset being visualized before the visualization interpretation. Due to these reasons, few works have been reported in the literature regarding botanical metaphors (Table 02).

5.2. *Metaphoric approaches to minimize the cognitive load on the human brain*

Cognitive load depends on the information processing demand on the working memory. Human perceptual and cognitive limits bound the ability to see and understand. According to the literature, these approaches can be broadly divided into 3D metaphor designs and interactions (Fig. 6).

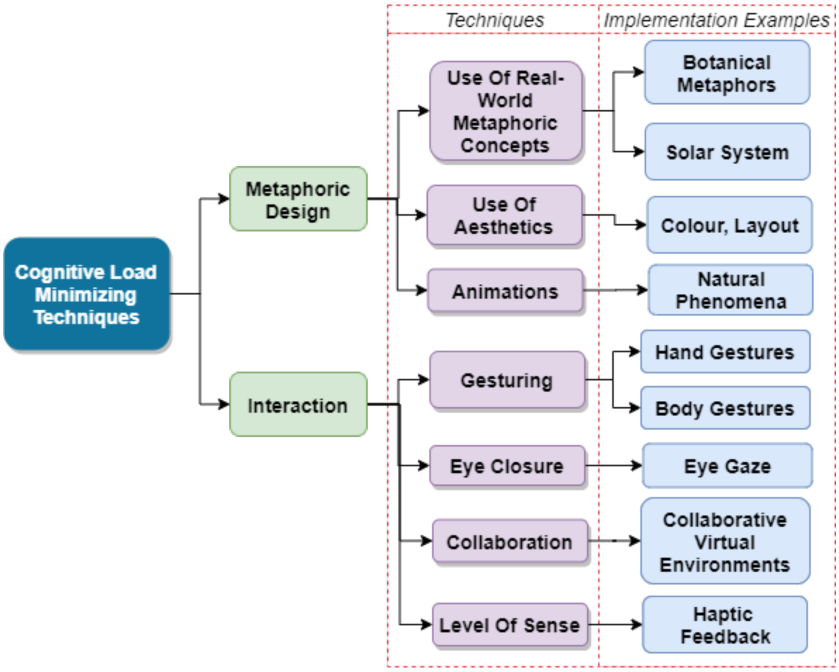

Fig. 6. Taxonomy of Cognitive Load Minimizing Techniques

Using familiar real-world metaphoric concepts can improve user experiences and learnability. Therefore, the user can intuitively understand the data visualization. For instance, cubes [34], fish tanks [39], and solar systems [12] represent real-world concepts.

Metaphoric data visualization promotes humans' efficient use of limited working memory resources to process new information. It allows more cognitive resources for information processing than mapping relationships. An empirical study has been carried out by Yi-Na Li et al. [82]. The results show that information comprehension is improved with glyph-based metaphors [78,79] (Table 01). Furthermore, natural phenomena [64] have been used as animation to decrease attention requirements. In addition, interactive information storytelling has been used to maintain active user participation in data analysis activities. Altogether it improves the level of user experience in visual data analytics.

Information visualization provides a captivating way of communicating information. Therefore, aesthetics is used to enhance the user's interest in engaging with data exploration while giving a realistic impression. Further, aesthetics is used to invigorate the mind and awaken the senses. For instance, aesthetics is highly applied in metaphoric worlds (Fig. 2) to provide a more natural environment. The use of colour themes and layouts is also common in data visualizations. The influence mechanism of aesthetics has been experimentally studied by Tian Lei et al. [85]. Their work involves the accuracy and readability of information delivery. Further, aesthetics helps to perceive ease in processing information.

The interaction techniques (Fig. 5) also evolved with the different metaphoric designs (Fig. 2). Interactive 3D metaphors allow users to engage with many different spatial interactions actively. Mainly the interactions originated with the keyboard and mouse. However, with the advancement of technology, more realistic interactions such as mid-air gestures, head tracking, and eye-gaze are made possible. Therefore, users can get a natural feeling when interacting with metaphors compared to traditional interactions. Anyway, the interactions have to be carefully selected to minimize the cognitive load. For instance, multi-touch gestures are more commonly used than touch-less gestures with handheld devices such as mobile phones and tablet computers. Therefore, metaphors designed for such devices may need to operate with multi-touch gestures. The following Table 1 summarizes the metaphor and the techniques applied to minimize the cognitive load in addressing the research question. The taxonomy in Fig. 6 depicts the different design and interaction techniques associated with metaphors to minimize cognitive load. However, it requires carefully selecting the appropriate metaphoric visualization and interactions to avoid confusion and ensure usability.

Different metaphors use different design and interaction techniques according to the datasets being visualized. Therefore, the following Table 1 represents how each metaphor incorporates cognitive load minimizing techniques in their metaphoric visualizations. However, some of the interactions, such as eye gaze to control objects, are not possible in real but in virtual reality.

Table 1. Cognitive load minimizing techniques

Metaphor	Cognitive Load Minimizing Techniques									
	Metaphoric Design					Interaction				
	Use Of Real World Concepts		Aesthetics		Animations	Traditional 2D Interactions	Gesturing	Eye Closure (Gaze)	Collaboration	Level Of Sense
		Colour	Beauty	Layout & Arrangement						
Galaxy Metaphor	√		√	√		√				
Solar System	√		√	√		√				
Room Metaphor	√		√	√			√			
Map Metaphor	√		√	√		√	√			
Topological Landscape Metaphor	√		√	√		√				
City Metaphor	√		√	√			√			√
Landscape Metaphor	√		√	√		√				
Forest Metaphor	√		√	√		√				
Space-Time Cube Metaphor	√			√		√				
Matrix Cube Metaphor	√			√		√				
Information Cube Metaphor	√			√		√				
3D Globe	√		√	√			√	√	√	√
Parallel Coordinates	√			√		√				
Fish Tank Metaphor	√		√	√	√	√				
Multilevel data glyphs	√		√	√		√				
AgentVis	√		√	√		√				
Tensor Glyphs	√		√	√		√				
Cone Tree Metaphor	√			√		√				
Carousel Metaphor	√		√	√	√	√				
3D Matrix Metaphor		√		√		√				
3D Helical Coil Metaphor		√		√		√				
Fire, Glove	√	√	√		√	√				√
`Neurite	√	√	√		√					
Brain Metaphor	√	√		√			√			√
Botanical Tree	√	√	√	√		√				
Family Tree	√		√	√			√			√
Book Metaphor	√			√		√				

5.3. Future Directions and Open Research Areas

Visual analytics of large complex datasets using 3D metaphors has been a focus of research within the last decades. However, designing 3D metaphors for ever-growing datasets is still challenging. Therefore, it requires novel metaphors for such data visualizations. Furthermore, theoretically, 3D metaphors claim unlimited design space. In addition to that, much of the existing knowledge for designing metaphors is not empirically sound about the cognitive system of humans [86]. Consequently, it requires reconsidering the traditional design principles and discovering novel, effective ways to adapt to minimize cognitive load. Therefore, there is still a need for more empirical research and guidelines on metaphoric data visualization in 3D.

Taking a step ahead, augmented and virtual reality have added much value to the 3D metaphoric data visualizations. Therefore, visual analytics of data is being approached like 3D game playing. However, it emphasizes the requirement of novel interaction to deal with metaphors and immersive environments. Therefore, the interactions trend towards direct manipulation with natural user interfaces. However, immersive visual analytics engage with a multitude of complex analysis tasks of different natures, leading to multifaceted interaction scenarios. Addressing this requires taking steps beyond the simple traditional direct manipulation techniques. Therefore, identifying and extending natural interactions would open a new area of research. A typical example of this is eye-gaze-oriented interactions. In the real world, eyes cannot control physical objects. However, it is made possible with virtual reality [87] and needs further research on improvements. In Table 01, it can be observed that the majority of cognitive load minimizing techniques are centred around metaphoric designs. Therefore, there are many opportunities to research novel interactions to minimize cognitive load. However, integrating multimodel controls such as gestures and voice to create more intuitive user interfaces is challenging in augmented and virtual reality.

The advancement in technology such as multisensory stimulation has made it possible to increase the degree of immersion, especially in 3D virtual worlds. Therefore, it opens another pathway to research adapting older visualizations to new technology. For instance, the degree of sense for direct manipulation can be improved with haptic devices [82, 83]. Therefore, empirical research is needed to evaluate the usability and effectiveness of novel visualizations.

Table 2. Types of 3D metaphors

Metaphor Type	Metaphor	Dataset type	Human-Computer Interaction Techniques	Exemplary Work
Composite Metaphors	***Metaphoric Worlds***			
	Galaxy Metaphor	Complex data, Real-time data	2D interactions Mouse and keyboard	[37,90]
	Solar System	Big data	2D interactions Mouse and keyboard	[12]
	Room Metaphor	Multidimensional data	Direct Manipulation, Ranged Pointing	[22,91]
	Building Metaphor	Network data	3D Interaction with HMD	[39,92]
	Island Metaphor	Large data	Direct Manipulation, Ranged Pointing	[15]
	Map Metaphor	Large data	2D interactions with keyboard, mouse, Swipe gestures	[31,46,93,95]
	Topological Landscape Metaphor	Time-Varying data	2D interactions Mouse and keyboard	[96,97]
	City Metaphor	Software production data, heap memory data, financial data	Direct Manipulation, Ranged Pointing	[6,12,13,14,16,17,18,98,99]
	Landscape Metaphor	Big data	2D interactions with keyboard, mouse	[75]
	Forest Metaphor	Multidimensional data	2D interactions with keyboard, mouse	[40,41,100]
	Geometrical Metaphors			
	Space-Time Cube Metaphor	Multidimensional data	2D interactions with keyboard, mouse	[29,30,101]
	Matrix Cube Metaphor	Multidimensional data	2D interactions with keyboard, mouse	[50]
	Information Cube Metaphor	Hierarchical data	Gesture interactions with DataGlove, HMD	[107]
	3D Globe	Multidimensional data, Geographic data	Tangible natural interactions with HMD	[46,47]
	Parallel Coordinates	Multidimensional data	2D interactions with keyboard, mouse	[42,43,44,71]
	Compound Objects			
	Fish Tank Metaphor	Network packet data	2D interactions with keyboard, mouse	[39]

Glyphs	Multilevel data glyphs	Large biomedical data	2D interactions with keyboard, mouse	[78,79]
	Hierarchical Glyphs			
	AgentVis	Multivariate data	2D interactions with keyboard, mouse	[29]
	Multivariate Data Glyphs			
	Tensor Glyphs	Tensor data	2D interactions with keyboard, mouse	[73,103]
Structural Metaphors	***Hierarchical Glyphs***			
	Cone Tree Metaphor	Hierarchical data	2D interactions with keyboard, mouse	[38]
	Circular Structures			
	Carousel Metaphor	Document metadata	2D interactions with keyboard, mouse, touch gestures	[104,105,106,107,108,109]
	Matrix Structures			
	3D Matrix Metaphor	Association rules	2D interactions with keyboard, mouse (zoom, rotation, sorting and filtering)	[56]
	Spiral Structures			
	3D Helical Coil Metaphor	Large data, Time dependent data	2D interactions with keyboard, mouse	[115]
Natural Phenomena as Metaphors	Fire, Glove	Trend data	2D interactions with keyboard, mouse	[64]
Biological Metaphors	`Neurite	Brain tissue data	2D interactions with keyboard, mouse	[65]
	Brain Metaphor	Multivariate data	Immersive 3D interactions with gestures	[81]
Botanical Metaphors	Botanical Tree	Hierarchical data	2D interactions with keyboard, mouse	[62,111]
	Family Tree	Hierarchical data	Touch Gestures	[117]
Other Metaphors	Book Metaphor	XML data	2D interactions with keyboard, mouse	[68]

With the aid of immersive technologies, there is a growing body of work on real-time analysis of data employing immersive visuals [7, 85-88]. Furthermore, collaborative visual analytics are favoured to collect insights into complex datasets collectively. Therefore, future research should explore the application of more advanced 3D metaphoric visualizations to promote combined data analysis. In addition, 3D Metaphoric visualizations can increase user engagement and improve memorability [94]. These factors are helpful to make information easily understandable. Further, achieving the same performance level in single-user environments is difficult in collaborative visual analytics in virtual environments.

Glyph-based 3D visualizations are primarily associated with clustering and positioning algorithms. Accurately placing the glyphs to present information is difficult in 3D space. In addition to that, it is challenging to avoid visual clutter in such 3D visualizations. Further, 3D glyph-based visualizations result in a higher data density, leading to occlusion. Therefore, it requires further investigation on finetuning the existing algorithms.

6. Conclusion

Metaphor-based 3D data visualizations have become popular in exploratory data analysis due to the rapid growth and complexity of modern datasets. Therefore, it has become critical to investigate the evolution of 3D metaphors with HCI techniques to minimize the cognitive load on the human brain. Many types of 3D metaphors have been proposed in the literature to visualize different data domains. However, there is a lack of recent literature reviews to get a comprehensive understanding of existing 3D metaphoric data visualization. Therefore, considering the current gap in the academic literature this paper contributes to advancing the present state of knowledge by studying and critically analyzing the recent literature on interactive 3D metaphoric data visualization with their application scenarios. Further, it also investigates modern cognitive load minimizing techniques associated with metaphors in the context of large data visualization in 3D. However, this article mainly reviews recent works from a data visualization perspective and involves only publications regarding interactive 3D metaphors.

Adhering to the PRISMA guidelines, this paper presents a systematic review of 3D metaphoric data visualization review. A comprehensive review has been carried out using a total of 60 publications in the field of interactive 3D metaphoric information visualization. Following the research question, metaphoric designs and interaction techniques are critically analyzed. Meta-analysis followed by a discussion highlights the strengths and limitations of the metaphors.

Metaphoric design and interaction techniques are significantly used to improve the efficiency and accuracy of visual data analytics. According to the characteristics of 3D data visualization metaphors, six main categories have been identified as composite, 3D Glyphs, Structures, Natural Phenomena, Biological and Botanical. This review points out the strengths and limitations of existing 3D metaphoric approaches. Further, this paper discusses possible pathways for further research on novel design and evaluation principles for 3D metaphor interaction techniques to increase usability while minimizing cognitive load. However, further work is required to evaluate the 3D metaphor design and interaction principles to minimize the cognitive load of visual data analysis.

The paper deeply examines the literature and contributes three taxonomies for different 3D metaphors, interactions and cognitive load minimizing techniques together with comparison results and discussion with exemplary work. Cognitive load-minimizing techniques used in 3D metaphoric data visualizations were identified and presented in a taxonomy (Fig. 6) and summarized in Table 1. Therefore, academics, practitioners and researchers can obtain valuable information for their future work. According to the analysis, composite metaphor designs and natural user interactions have higher demand in data visualization in 3D. However, virtual reality platforms attempt to combine metaphoric concepts with the latest interaction technologies while providing more realistic 3D data visualization environments. Further, VR-based immersive multi-user 3D metaphors can be identified as an emerging area of research under collaborative data exploration. Overall, it shows a strong need for novel intuitive 3D metaphors for interactive visualizations to better insights into modern complex datasets. Therefore, it is still an open area for future research. This systematic literature review paper can be served as a better reference point for future research.

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Authors’ Profiles

A.S.K. Wijayawardena has completed his BSc. (Hons) in Information Technology from Sri Lanka Institute of Information Technology, Sri Lanka in 2006. Then he obtained his MSc. in Computer Science from the University of Moratuwa, Sri Lanka. Currently, he is reading his MPhil degree at the University of Colombo School of Computing, Sri Lanka. He has six years of experience as a Lecturer at the University of Vocational Technology. His research interest areas comprise data visualization, big data analytics, and metaphor-based information visualization

MWP Maduranga obtained his BSc.Eng. in Electronic Engineering degree in 2013 from the Asian Institute of Technology(AIT), Thailand, and MS.c.Eng in Electrical and Electronic Engineering degree from the University of Peradeniya, Sri Lanka in 2017. He received his Ph.D. degree in Computer Engineering from the IIC University of Technology, Cambodia in 2023. He is also a senior member of IEEE and received Engineering Charter in Electronics and Telecommunication Engineering from the Engineering Council, the UK in 2020. His current research interests include Machine Learning based indoor localization, AI/ML in IoT applications, and wireless communication.

Ruvan Abesekara obtained his Ph.D. in Computer Science and Technology from Dalian Maritime University, China, and holds an MSc in Computer Science from the University of Colombo School of Computing. He is currently a professor in computer science and the vice chancellor at the IDM Campus, Sri Lanka. He also serves as a visiting researcher at the IIC University of Technology, Cambodia. In addition to his academic qualifications, Ruvan holds several industry and professional certifications. He holds membership in several organizations such as The Institute of Doctors Engineers and Scientists, the Institution of Engineering and Technology, the Institute of Electrical and Electronics Engineers, the British Computer Society, the Chartered Institute for IT, the Computer Society of Sri Lanka, Australian Computer Society, etc. Also, He is a Microsoft Certified Peer Coacher and Cisco Certified Instructor. His current research interests include data mining and algorithms, IoT.

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