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Chapter 3
Cognitive Data Visualization—A New Field with a Long History

Zsolt Győző Török and Ágoston Török

Abstract Cognitive data visualization is a novel approach to data visualization which utilizes the knowledge of cartography, statistical data representation, neuroscience and ergonomic research to help the design of visualizations for the human cognitive system. In the current chapter, we revisit some benchmark results of research in cartography in the last half a millennium that shaped the ways how we think of and design visualizations today. This endeavor is unique since typical earlier reviews only assessed research in the past century. The advantage of our broader historical approach is that it not only puts cognitive data visualization in wider cultural context, but, at the same time, it calls attention to the importance of reconsidering the proceedings of earlier scholars as a crucial step in directing exploratory research today. In this chapter, we first review how conventions in data visualization evolved in time, then we discuss some current and pressing challenges in modern, cognitive data visualization.

3.1 Introduction

The methods of effective visual communication has been in the focus of research within various fields, from cartography to statistics in the past decades [1–3]. Numerous benchmark books and several papers endeavored to describe the principles of visual representation of information and authors have recommended practical hints

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how to assemble, analyze, and present collections of data. These principles, however, were rarely based on experimental knowledge about the human cognitive system. Although recently the accumulated knowledge about human memory and attention (how much information we can process), emotion (Kahnemann and Tversky) and perception (affordance, Gestalt principles) has begun to affect our views of the ideal way of visual infocommunication, there is still a lot to do. While data visualization has improved significantly, we need to reconsider traditional design principles and find new and effective methods to adapt to the new challenges of cognitive infocommunication [4, 5], namely virtual and augmented reality [6].

Nowadays, emerging technologies facilitate the need of revisiting and extending data visualization guidelines. As data dashboards, interactive visualizations, and mixed reality data displays are becoming widespread the guidelines developed for static, low dimension visualizations has to be adapted to help researchers and practitioners from various fields in creating effective visuals with new technologies. This endeavor is especially important since the price of generating massive amount of data is rapidly increasing, and visualization tools struggle hard to keep up with it [7].

Most books on visualization are dealing with the challenge if how to present the results of statistical or spatial analysis, however visualization actually serves various purposes:

- explore patterns, structures, relations in mass data
- present results of some analysis visually
- support human decision making with graphical interface.

Visualization is therefore a multifaceted tool. As such, forms of visualization does not only include graphs and charts, but also maps, dashboards and other interactive visualization types as well. However it is more than a simple graphical display of raw data. It always includes some kind of abstraction, either in the form of interpretation or simplification. From visualizations users can derive information and knowledge (Table 3.1).

In the following chapter, we first overview the history of graphical methods of visualization and revisit the historical material and the empirical results of practice that helped modern scholars in establishing the principles of data visualization. Thereafter we discuss the challenges raised by the emerging new technologies, and third we formulate an updated set of guidelines that can be applied to data visualization.

Table 3.1 Difference between data and visualization

Data	Visualization
Nonstructured	Structured
No communication purpose	Communication purpose
High resolution	Low resolution
Not interpreted, meaningless	Interpreted, meaningful
As is	Designed

3.2 History of Visualization as a Cognitive Tool

The ability to represent objects or concepts in the external world goes back to prehistory [8]. Rock carvings or cave paintings from different parts of the world demonstrate the important development steps in the human cognitive system. The fundamental issue here is the appearance of the ability to represent something with meaning, reflecting the intention of the human subject. In other words, the external representation and the internal representation (i.e. thinking) had to be linked somehow in one system, material culture. Although our knowledge about the beginning of the use of external representation as a cognitive tool is rather limited, the earliest examples of identifiable, 'meaningful' images were presumably created by *Homo sapiens* more than 12,000 years ago. According to the theory of cultural evolution by Donald [9], this was a decisive invention in human history and meant the dawn of material culture and the end of the mimetic and the episodic eras.

3.2.1 *Visualization as a Form of Externalized Memory*

From the beginning external representations were projections of the human mind. In particular, they served as an expansion of biological memory: their appearance made it possible for early societies to accumulate and transfer knowledge. It is important to note that, once materialized, the constituents of any graphic bear also spatial attributes. The graphic space of a representation becomes part of the system which is inherently spatial. This is why *mapping* or, in its more developed form, map making is considered here as archetype of *any visualization*. However, one should keep in mind that not only have been maps simply used as visualization tools by highly diverse human cultures for thousands of years. Working with diagrammatic space had tremendous effects on human minds in the course of history leading to modern societies, where map use is common in spatial problem solving. The effective instruments of visualization have made humans able to explore, beyond their geographical environment, large, inaccessible or complex sets of objects, phenomena or even abstract concepts.

Drawing on the definition proposed by Harley and Woodward [10], maps can be interpreted as graphic designs that facilitate a spatial understanding of things, concepts, conditions, processes and events in the human world. This functional approach is in contrast with the professional definitions focusing on the form, structure and content of the modern map. Although these may describe the most important, contemporary types of maps, it is historically misleading to apply modern criteria to all kind of mapping. Indeed, as a social practice mapping was never a monolithic enterprise—how it is suggested by traditional stories about developments of cartography [11]. On the other hand, mapping was always based on the relations between the external representation space and its graphic objects on one side, and also on the internal processes of the human mind on the other.

3.2.2 *The First Map*

Although the pictorial form of some modern maps may suggest so, historical evidence shows that early maps were highly abstract graphic representations. The first maps made by humans were presumably ephemeral and has not survived. The Mesopotamian clay tablet from c. 2300 BC is generally considered to be the earliest uncontested. It demonstrates how advanced cartographic principles had been applied by the unknown maker of that more than four thousands years old instrument. As the cuneiform script reveals, its direct function was to depict the location of a land property in the geographical context of ancient Mesopotamia. The graphic language, the symbols for water flow, mountain range or settlement are, although abstract in form, easily recognizable for a modern reader who can understand geographical concepts from this very early artifact. The same clay tablet exemplify another remarkable characteristics of cartographic visualization: although a property map the two-dimensional representation is oriented according to the cardinal directions, which were originally marked on the sides. In other words, the first map survived is strong evidence that a universal, geographical reference frame has been used by human civilizations for more than four thousands years.

3.3 History of Graphic Methods

Although map making looks back to a long history, as a regular and systematic social practice it is closely related to the early modern period. In the past five hundred years graphic representation became a common tool to visualize highly complex systems and solve various problems using maps, charts, plans and diagrams. Medieval maps demonstrate the transfer of geographic information and knowledge about methods of data visualization [12]. However, the most common type of world maps, the circular maps also evidences for the importance of social-cultural aspect of visualization.

3.3.1 *Early Forms of Infographics*

The usually small size and diagrammatic depictions of the division of land and water according to the Bible clearly display the geographical arrangement of the known continents and their spatial relations. Though, the simplicity of the graphic design may be misleading for the modern reader, who is not familiar in Christian symbolism. But one must note that the waters dividing the land form the letter 'T' (*terra*), here also a symbol for the Crucifixion. It is placed in the middle of the circle of the ocean, making a letter 'O' standing for the Latin word '*orbis*', world. Simply drawing these two letters, arranging them this way in the graphical space, medieval scribes would not only draw an initial with map of the world: they also told the reader the whole story

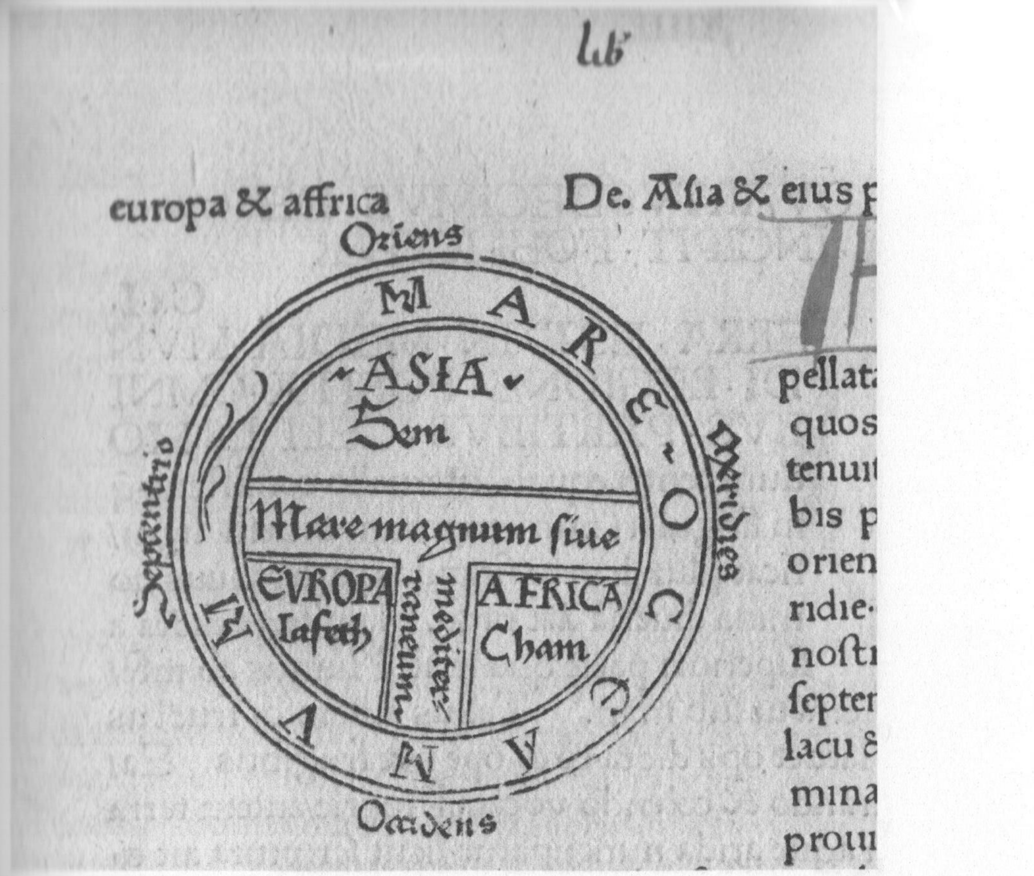


Fig. 3.1 The first printed map: a diagrammatic representation of the Christian Universe (Augsburg, 1472)

of the creation of a Christian Universe. The abstract letters interpreted as a diagram, as a representation in a graphical space, convey much information about the spatial structure, the geography of the world. If it was made today, it was considered an infographics rather than a real map (Fig. 3.1).

3.3.2 *Visualization Before Conventional Signs*

Signs and symbols on the map, in the graphic space, are located in a spatial reference system and this is the fundamental advantage of graphic representation over verbal or written description. On early modern maps one can find great variety of pictorial and abstract signs, which makes interpretation sometimes difficult. Although the

Fig. 3.2 Wilhelm Crome's economic map of Europe with symbols

signs standing for the same object are similar, each map maker could use its own version. The lack of convention in the sign systems used is a striking characteristics of early modern maps. 16–17th century maps often represent information which is not directly visible in the field and stands for the quality of objects. Signs could be referred to points, but could be distributed to represent the spread of the same type of qualitative information, usually a category (e.g. forest). The distribution of languages on each continents on Gottfried Henschel (1741) or the pioneer 'geognostic' maps by Jean Etienne Guettard demonstrated how early visualization could make invisible, inaccessible objects or phenomena visible and easy to comprehend [13]. By the 18th century scientific research or statistical surveys resulted in large collections of data, including both qualitative and quantitative information.

In 1782 the German economist and statistician Wilhelm Crome published a map of Europe (Fig. 3.2), showing the major products of the countries by signs and letters. A few years later Crome produced a series of comparative diagrams [14] showing the size and population of states in Europe in graphic form. In 1818 he published his

Fig. 3.3 The legend on Korabinszky's pioneer economic map of the Kingdom of Hungary (1791)

first economic map in a new edition with additional pie charts, another contemporary graphic invention.

The first thematic map of a country, Johannes Korabinszky's 1791 map of Hungary, depicted national economy by using 92 different signs and symbols. The information was taken by the author from his own geographical-economic lexicon (1786), an early collection of economical and statistical data (Fig. 3.3). The visualization of the some 15,000 entries, represented by the miniature signs on the map, although neither spectacular not very effective, was highly appreciated by the rational minds of contemporary scholars. Korabinszky's pioneer thematic map was not only used by the traveler and naturalist Robert Townson in 1797, but he added the mineralogical information he collected in the field in 1793 to the map in a new layer. This is a remarkably early example of multiple and interactive visualization.

3.3.3 *Coordinates, Charts, Diagrams*

Similarly to the geographic coordinate system, which has been in use already in the Antiquity, the graphic visualization of phenomena in a planar coordinate system was already known in the Middle Ages. The 14th century Italian mathematician, Nicole

Oresme explained concepts like time, velocity, distance in a graphical way, using simple *graphs* . The method of modern analytical geometry was introduced by René Descartes in 1637 [15].

In 1765 Joseph Priestly published 'A Chart of Biography' [16], which represented temporal data: the dates of birth and death of important persons were connected to create a *stick chart*. The representation of statistical data by *diagrams* was the novelty of William Playfair's 'The Commercial and Political Atlas' [17] (Fig. 3.4). Although it was called an atlas, the economic data was represented not in maps but by the method called 'linear arithmetic', which meant graphs. Playfair's books were published in different editions and these publications made the methods of statistical data visualization, graphs and diagrams, available for scholars of the 19th century.

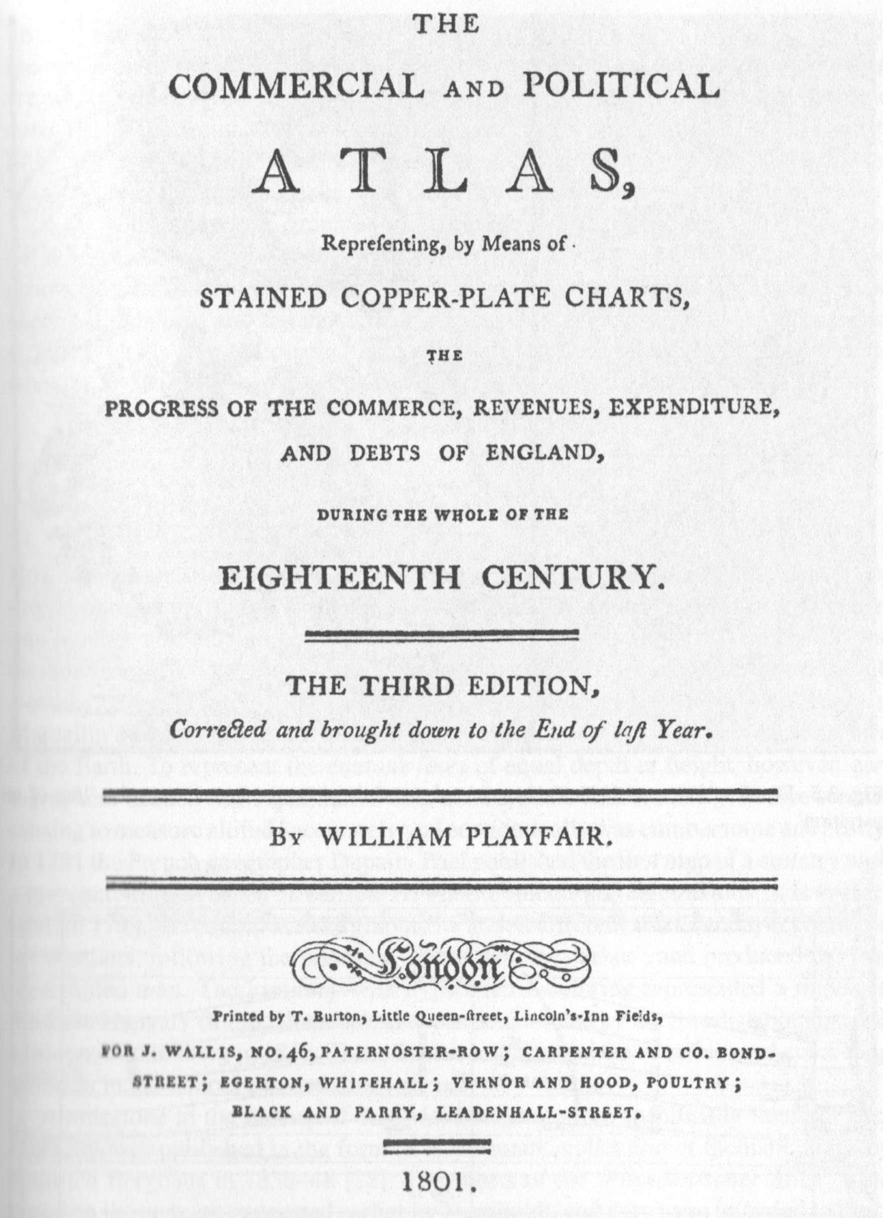
3.3.4 The Emergence of Isolines

Edmond Halley is generally considered by historians of cartography as the first thematic cartographer, especially because of his highly influential charts showing the variations of the compass [18]. The novelty of these graphic representations was not only the representations of magnetic declination, but also helped finding the geographical position of ships in the oceans. Halley, who collected magnetic data during his journey in the Atlantic, selected to show the variation of the magnetic compass by 'curve lines', running across points with equal declination (Fig. 3.5). As the magnetic field is a *continuum*, the graphic invention of the *isoline*, a line connecting points of equal value, made map makers able to represent all kind of continua. This technique is now widely used in other fields too, for example in the form of contour plots.

Modern thematic maps similarly represent the spatial distribution of objects or phenomena in the geographical or abstract spaces. For spatial reference a background map is needed and the map theme is layered above that. These types of maps are in contrast both conceptually and graphically with the general map, which shows the spatial location of a set of geographical objects (settlements, rivers etc.) and serves orientation and navigation. One of the most important followers of Halley was Alexander Humboldt, who published his treatise in 1817 with a diagrammatic chart showing the global distribution of temperatures by using lines of equal value, *isotherms* [19] (Fig. 3.6).

3.3.5 Flow Lines

Halley's first thematic map, his 1688 wind chart, also brought a remarkable novelty. The *dynamic* phenomena was symbolized by small strokes. As the author explained, these represented the ship sailing with the wind behind, the direction of the wind was shown indirectly by the narrowing end of the lines. This was a remarkable



THE

COMMERCIAL AND POLITICAL

ATLAS,

Reprefenting, by Means of

STAINED COPPER-PLATE CHARTS,

THE

PROGRESS OF THE COMMERCE, REVENUES, EXPENDITURE,

AND DEBTS OF ENGLAND,

DURING THE WHOLE OF THE

EIGHTEENTH CENTURY.

THE THIRD EDITION,

Correcled and brought down to the End of laft Year.

BY WILLIAM PLAYFAIR.

London

Printed by T. Burton, Little Queen-ftreet, Lincoln's-Inn Fields,

FOR J. WALLIS, NO. 46, PATERNOSTER-ROW; CARPENTER AND CO. BOND-STREET; EGERTON, WHITEHALL; VERNOR AND HOOD, POULTRY; BLACK AND PARRY, LEADENHALL-STREET.

1801.

Fig. 3.4 The title page of Playfair's statistical atlas (1801)

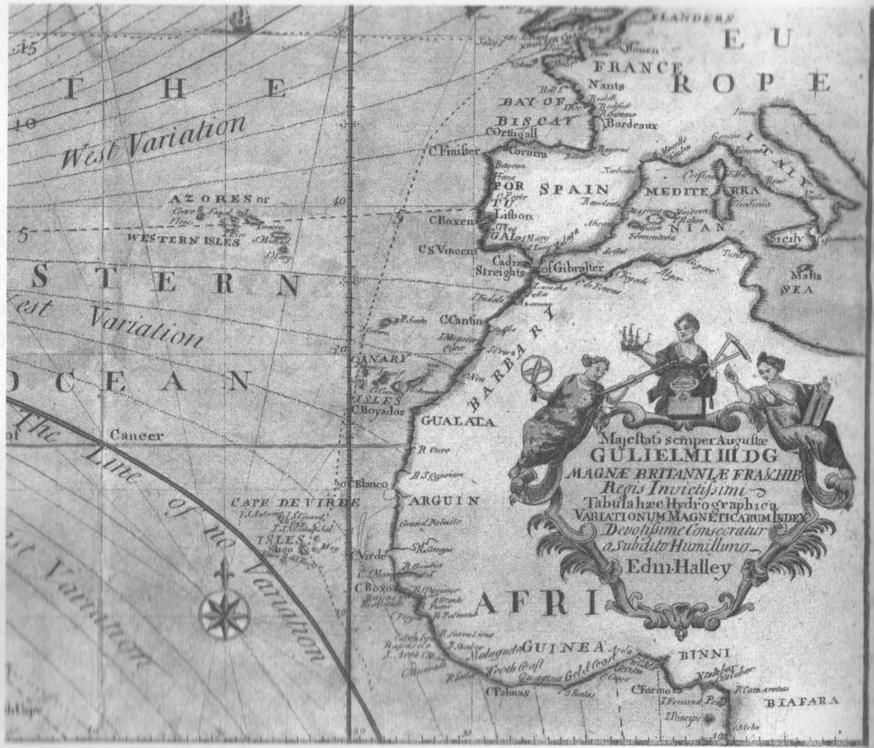


Fig. 3.5 Detail of Edmond Halley's isogonic chart of the Atlantic Ocean: note the 'line of no variation'

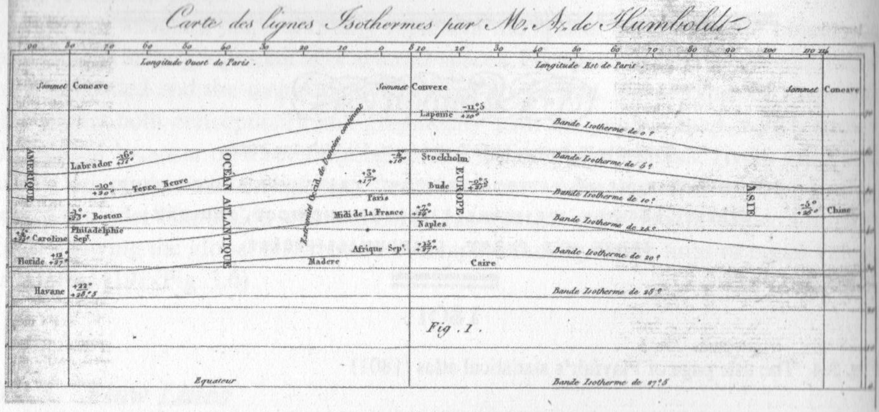


Fig. 3.6 Alexander von Humboldt 1817 chart showing the distribution of average annual temperature

invention to show movement on a static map by *flow lines*. Navigational charts with the direction of the winds appeared regularly in the 18th century, usually applying arrows, of which a few appeared on Halley's chart as well. Another early example designed by the Jesuit scholar Athanasisus Kircher (1665), or the German novelist, Eberhard Happel's 1685 chart displayed the water circulation of the world oceans with streamlines, but, curiously, without direction arrows.

In the 19th century the graphic representations of social and economic activities could use detailed statistical data bases in France, where Charles Joseph Minard produced a series of highly inventive flow charts. He was interested in international economic relations and the movements of a wide range of subjects from people to products. Of his maps, '*carte figuratives*' Minard published some ten thousand copies from the 1850s and his graphic methods became known by a wider public [20].

3.3.6 *From the Depth of the Sea to Population Density*

However, one must note that isolines appeared much earlier, already in the 16th century to show the depth of water in a river in the Netherlands (Bruins 1584). After this pioneer visualization it took almost two centuries to expand the scope of the method from rivers and seas to continental areas. After important publications with isobaths (e.g. Marsigli 1725, Buache 1752 referenced in [2, 21] in 1782 Bonifas Marcellin du Carla proposed the general use of isolines to show the physical surface of the Earth. To represent the *contour lines* of equal depth or height, however, cartographers needed mass qualitative data about relief. Unfortunately, before remote sensing to measure altitude accurately and economically was cumbersome and costly. In 1791 the French geographer Dupain-Triel published the first map of a country with a few contour lines based on barometric measurements and calculations. A few years later, in 1798–99, to enhance the graphic he added different shades to layers between his contours, following the principle 'the higher the darker', and produced the first layer-tinted map. The first map with hypsometric coloring represented a region in northern Hungary (today Slovakia), and was constructed by the Swedish botanist and explorer, Wahlenberg in 1813. These traditions triggered the use of several color-map schemes in contemporary visualization.

A milestone in the history of data visualization, more specifically thematic cartography, was published in the form of a systematic collection of thematic maps by Heinrich Berghaus in 1838–48 [22]. The sheets of the '*Physikalischer Atlas*' were based on the concept suggested earlier by Humboldt, and they were intended to illustrate his ambitious physical description of the world (Fig. 3.7) five volumes of his '*Kosmos*' (1845–62). To portray meteorological, geophysical phenomena, but also plant geography or anthropogeography a wide variety of data visualization techniques were used by the designers of the maps, including isolines, diagrams and graphs. *To demonstrate quantitative data by lines of equal value, based on the interpolation*

Fig. 3.7 Choropleths and isolines combined in a complex thematic map in Berghaus' atlas (1840)

between localized observations or measurements points became a common place by the mid-19th century. To depict more abstract, e.g. statistical phenomena was the next step. This was proposed by Lalanne in France [23], who extended the ideas of du Carla and Humboldt to statistical data, which was considered as a third dimension superimposed on the general map. In 1857 the naval officer Ravn published such a map [24], showing the density of the population in Denmark by *pseudo-isolines* and using colour tints for his 500 person per square mile intervals. As the result of the evolution of the graphic methods of data visualization a highly effective new method was created, the *isopleth*. Although graphically similar, the *choropleth* represent data related to pre-defined regions or areas (e.g. nodes belonging to the same cluster) whereas *isopleth* is based on quantitative data located to points (e.g. degree of a nodes).

3.3.7 *Visualization for the Public: Geographical and Abstract Spaces*

By the mid-19th century both the physical surface of the Earth and abstract, statistical surfaces could be represented cartographically, using the same graphic methods, isolines and layer tinting. Despite their simple visual appearance these representations were based on rather sophisticated concepts. For example hypsometric relief representation was used only at small scales because it required a precise measure of altitudes, which before air photogrammetry was cumbersome. Thematic cartography also depended heavily on reproduction methods. The introduction of a new printing method, lithography, made graphical reproduction faster and cheaper in the early 19th century. Another advantage, chromo-lithography offered color printing, and this technical invention had great impact on the distribution of data visualizations in public media.

From the mid-19th century international conferences advanced the emerging discipline of statistics [25]. The graphical methods of data representation were explored and discussed in Wien in 1857, where the maps of Josef Bermann or Carl Czoernig were also displayed. The connection between topographical and thematic map making is best exemplified by the participation of Franz Hauslab, a military cartographer, who proposed the principle 'the higher is the darker' for hypsometric representation

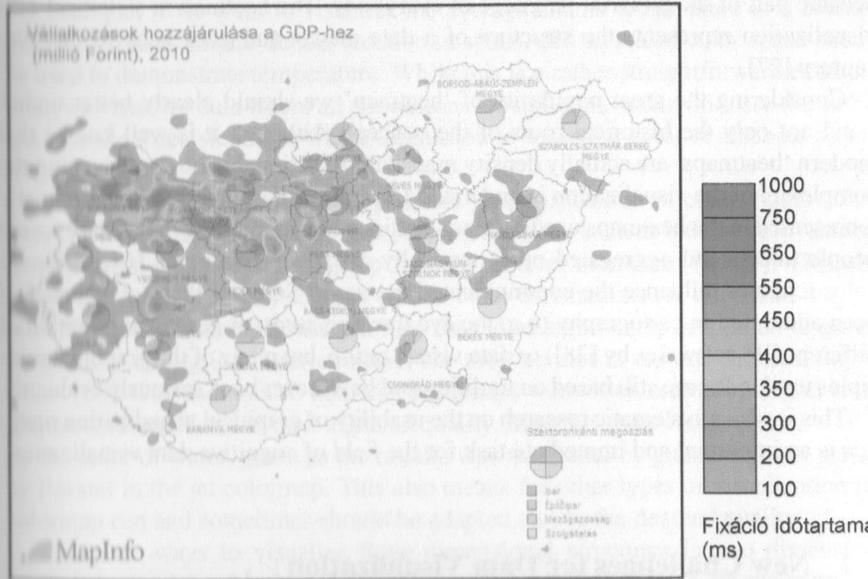


Fig. 3.8 Eyetrack data visualized with hypsometric color scheme (so called 'natural colors')

of the relief (Fig. 3.8). Later special committees regularly reported to the plenary session about graphical methodology issues, first of all categorization and the use of colors.

3.3.8 *Cool Heatmaps and Cognitive Issues*

In 1885 Émile Levasseur [26] proposed to demonstrate deviation of mean values: red for categories above and blue for categories below the average, giving birth to the jet colormap. This approach had its roots in the antique traditions of cartography, warmer colors were used for land surface and cooler, usually blue and green, colors for waters. This tradition and later convention demonstrates also how real world inspiration drove color choices in visualization. As a reflection to scientific advancements thematic maps were included in general atlases, showing e.g. the global distribution of temperature. Already Humboldt suggested to show summer and winter average temperature (isotheres and isochimenes).

From the meteorological data a statistical surface was created, and the intervals between the *isotherms* were colored according to a legend (i.e. colorbar). These were the real heatmaps, and for the associative use of color, anybody would understand which parts of the world were the warmest or the coldest. Similar maps appeared in school atlases everywhere and the graphical presentation methods of scientists became part of the pictorial language of everybody. The heatmap in statistical data visualization represents the structure of a data matrix and goes back to the 19th century [27].

Considering the great popularity of 'heatmap' we should clearly better understand not only the historical roots of the concept. Although it is well known that modern 'heatmaps' are actually density maps, it is questionable how much about the complexity of the visualization is understood by non-professionals. What is actually represented in the heatmaps used by visualizations of eye tracking data? How would people understand aggregated or dynamically displayed fixations? How different color schemes influence the communicated message? Some of these questions had been addressed in cartography (e.g. the eye tracking study of graphical potential of different GIS softwares by [28]) or data visualization, but many of the graphical principles used today are still based on tradition and have never been seriously evaluated.

This is why a systematic research on the usability of graphical visualization methods is an important and immediate task for the field of cognitive data visualization.

3.4 New Challenges for Data Visualization

For a long time, data visualization has been constrained to two dimensions and was static in format. Both traditional, analogue media (e.g. paper) and the computer screen are primarily suitable for visualizing data in two spatial dimensions. This

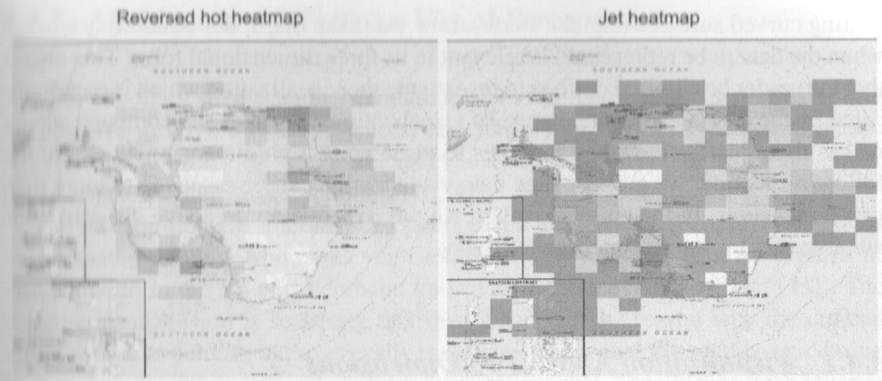


Fig. 3.9 Visualizing eyetracking data using a reversed hot colormap and the frequently used jet heatmap

does not necessarily mean that more dimensions cannot be represented here, it is adequate to say, however, that visualization in higher dimensions require steps of abstraction, both from the author's and from the reader's side. For example, as was described earlier, heatmaps are used in several domains today. In the simplest case, the heatmap uses colors to represent a third dimension. While this is a very useful feature, it works best if the color dimension denotes a qualitatively different measure. For example, if we want to visualize the average annual temperature in a country, the x and y axes should denote location in space, and an added color space should be used to demonstrate temperature. While this is a rather straightforward example, often we visualize data where all dimensions are different, and in this case the author has to make a decision as to which dimension to select for color or attribute coding (Fig. 3.9).

Another challenge with heatmaps is the proper selection of color. Some colors have conventional associations. However, associations such as blue is 'cold' and red is 'hot' are not innate, but develop through cultural influence [26, 29]. This also means that while it is easy to think that all color associations are universal, they are possibly not. For example, associations for red as sign to stop and green to go are particularly strong in western culture, but they are not in eastern cultures, e.g. in China [30]. One should also note that colormaps were often created to depict some graphical resemblance to their signaled quality. Blue for lower values was motivated by the color of water, green as the middle was motivated by grass, whereas yellow by the sun in the jet colormap. This also means for other types of visualization the colormap can and sometimes should be adapted also to the denoted quality.

There are ways to visualize three dimensional structures in two dimensions through projections. Mesh plots, contour plots and surface plots are the most frequent of these, but their use is usually not preferred because due to the nature of projection some parts of the image are not visible unless rotated, which option is rarely available for traditional data visualizations. This is not an issue when representing curved surfaces (e.g. the Earth), how we make maps, but issues may emerge when the data to be represented is relevant in its three dimensional form. This means that the reader has limited options to investigate the visualization which is communicated by the author. The static nature of visualizations on paper and computer screen makes them ineffective when it comes to visualizing high dimensional data. In the following section, we propose how data visualization can be extended to more than two dimensions. In the end we explain why dynamic and interactive visualizations are essential for human intelligence today.

3.4.1 *Visualization Above Two Dimensions*

The perception of the world around us is essentially three dimensional. The human visual system developed to render the three dimensional information of the environment in the mind. This not only means that we perceive depth information despite the two dimensional nature of the optical image on the retina, but, more importantly, our perceptual system has adapted to the challenges of the physical world. So to speak, the framework of embodied cognition [31] claims that the cognitive system is inseparable from the body [32] and the environment [33]. This evolutionary developed fit between our cognition and the environment makes us able to cope with the vast amount of information reaching our senses at any given moment [31] and quickly react to new information in the environment [34].

3.4.2 *Ultra-Rapid Visual Categorization*

Embodied cognition is the reason why processing information presented in forms that are not present in nature takes more time and are not straightforward to interpret. Oddly, this suggests that carefully designed two dimensional graphs may take more time to process than a more natural three dimensional scene. This notion is supported by the results of several studies investigating ultra-rapid visual categorization [35–39]. These studies consistently find that complex natural scenes displayed for milliseconds can be categorized under 150 ms as it is revealed by both EEG evidence [38] and saccadic reaction times [39]. Further studies showed that people can process even multiple scenes in parallel with this speed [37], which means that no directed attention is required. Furthermore, ultra-rapid categorization of complex natural scenes is not only highly automatic but is not affected by the familiarity of the exact pictures [36]. Thus, this phenomenon clearly indicates that the visual system is adapted to the complexity of the visual world; consequently, the natural-unnatural dimension is far more important in perception than the simple-complex one.

3.4.3 *Multisensory Effects on Visual Perception*

Another corollary of the embodied nature of the human cognitive system is that we perceive through all of our senses, and sensory modalities can facilitate each other. Such multisensory enhancements causes decreased reaction times and better performance for multisensory stimuli [40, 41].

The most prominent multisensory phenomena are the visual capture of sounds in the spatial domain, known as ventriloquism [42]; and the auditory capture of visual stimuli in the temporal domain, known as the illusory-flash effect [43] . The ventriloquism illusion is so strong that this is actually the reason why the cinema experience is so natural: our eyes easily makes us believe that the sounds are coming from the mouth of the actor and not from the speakers [44]. The illusory-flash effect is a little less trivial. In the typical experimental situation one flash is presented with two short beep sounds, of which one is concurrent with the flash. The resulting percept is two beeps *with two flashes*. These results show sensory stimulation in multiple modalities interact and shape the final percept. Nevertheless, in both of these cases we were aware that auditory and visual stimulation was also present.

In data visualization these factors may not take a significant role since we usually design visuals and not synchronized stimuli in another modality. However, this is only partly true. Curiously enough, multisensory effects are present also in situations where one would not expect them. There is actually one organ of sense people usually forget about—despite being the most fundamental percept in life. This is the vestibular sense and its contribution to the perception of up and down directions. Our primary senses, eyes, ears, nose, skin, and tongue are all easily observed and have been studied since ancient times. The vestibular sense, however, is located in the inner ear and was discovered only in the beginning of the twentieth century by von Bárány [45]. This is responsible for our sense of balance [46] and contributes to bodily awareness [47]. Studies investigating the neural underpinnings of vestibular sensation found that although there are areas dedicated to vestibular processing, vestibular afferents reach several areas throughout the cortex [48]. Therefore, despite being often subconscious, the vestibular sensation modulates the perceptual processes in other sensory modalities.

One striking example of this is the interaction between visual and vestibular sensation in visual distance perception [34, 49–51]. These studies show that the same visual distance is perceived differently depending on the position of the body [49, 50], the head [34] and the eyes [51]. Things above the horizon seem afar while things below that seem closer. There are reasons to believe that the direction of the effect is in connection with perceived effort [52], but is present also when no effort is included in the task [34]. The effect is also nonlinear: experiments dealing with unnavigable angles (90°) found that because of fear of falling the effect reverses for these extreme angles. From the scope of the current review, the relevance of these results is that the size and layout of a visualization may easily distort the perceived differences between two figures. Since visual distance is inferred from the perceived size and known real size of the object [53] one can easily deduce, that any change in the perceived distance of the same object means change also in the perceived size since the known size cannot change.

The vestibular perception of gravity affects visual information also on another level. Difference in the speed of motion of an object is differentiated more accurately when the motion is consistent with gravity [54]. Also, even memory for gravity consistent motion is biased [55]. This is most easily seen when in an experiment the participant is required to show the location where an object has disappeared. They consistently find that people show below the location where the object actually disappeared when the motion was consistent with gravity.

The relevance of these effects to data visualization is emphasized for map-like dynamic visualizations. As North is traditionally associated with up and South is associated with down in cartography, this cultural convention shapes our perception of the world. Although we may think it was always so, before the early modern age different orientations were used in cartography. This may have been related to human values maps always presented. Not only size differs on the vertical axis, other studies showed that "up" is associated with good, profit, and higher altitude, whereas "down" is associated with bad, prices, and lower altitude [56–59]. The down-up visual axis is also associated with hierarchy and development. Furthermore, our memory of the world map is biased in the location of the home continent, which is usually remembered larger than actually. Also, Europe is remembered as being larger while Africa as being smaller than its actual size [60]. The strength of the verticality effect can be easily seen if we look at a map where South is associated with up (see Fig. 3.10). Little known is the fact that, although orientation to the North goes back to the mathematical astronomical tradition of geography represented by Ptolemy in the 2nd century AD, until the early modern age maps were oriented to various other directions. Medieval Christian cosmographic diagrams had 'Oriens' at the top (and hence the word 'orientation'), while Islamic cartography adopted South as the primary direction. Even in early modern Europe, after the rediscovery and adoption of the Ptolemaic method appeared maps with other orientations. A famous example is the series of south-oriented, anthrophomorphic maps from the 16th century, representing Europe as a Queen (see Fig. 3.10)

3.4.4 *Visualizing in Three Dimensions*

There are two areas where three dimensional visualization is especially helpful and already in common use. These fields are architectural design and medical imaging. In architectural design computer generated renderings are used for presentation, marketing, and design purposes. Here three dimensional, more realistic visualization greatly supersedes the use of two dimensional plans. These virtual copies are often used for simulating different light and environmental conditions, and panoramic and renovation effects [61]. As abstract and symbolic representations of the real world architectural renderings are often considered outside of the traditional scope of data visualization [3], but they should be included as data visualizations. Moreover, the

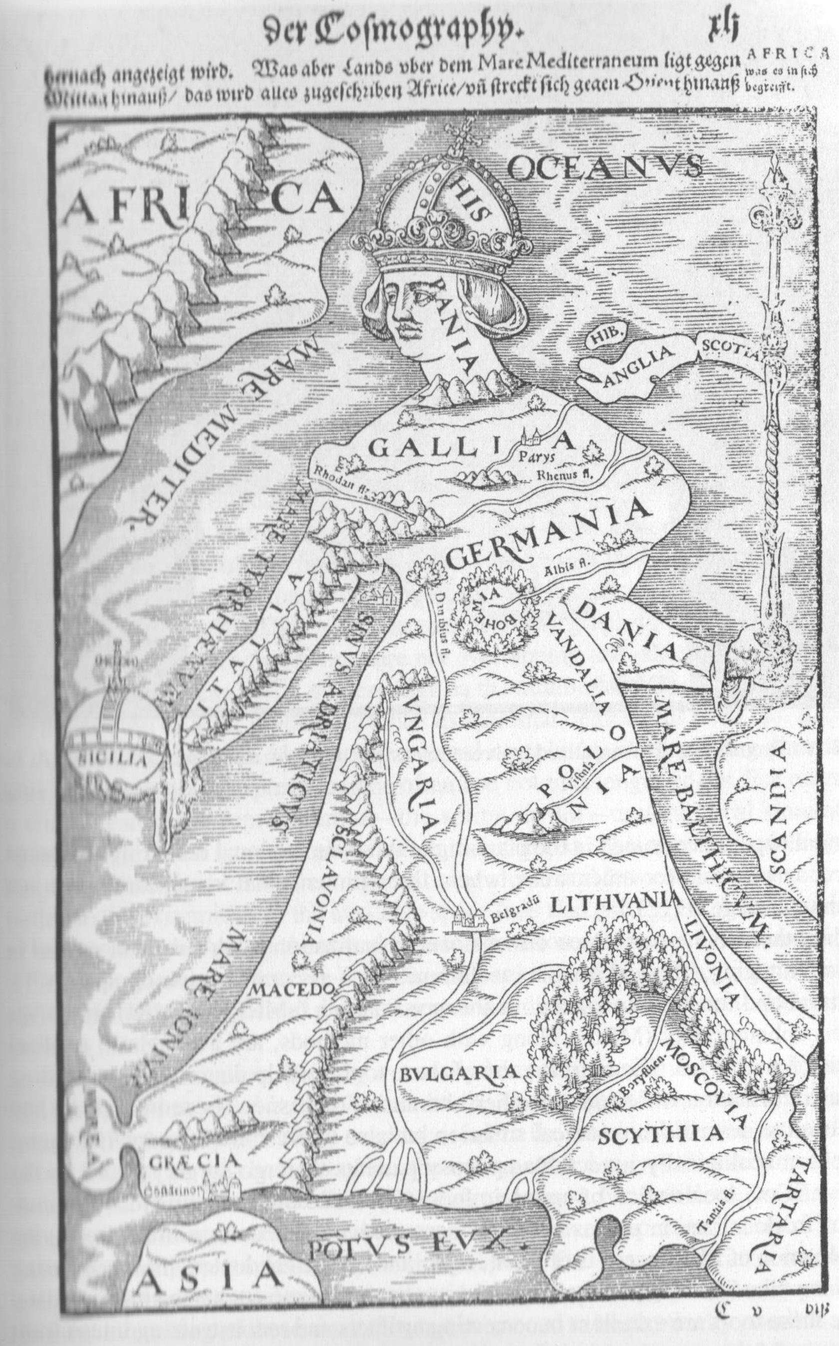


Fig. 3.10 Queen Europe as a map oriented to the West (Sebastian Münster, 1588)

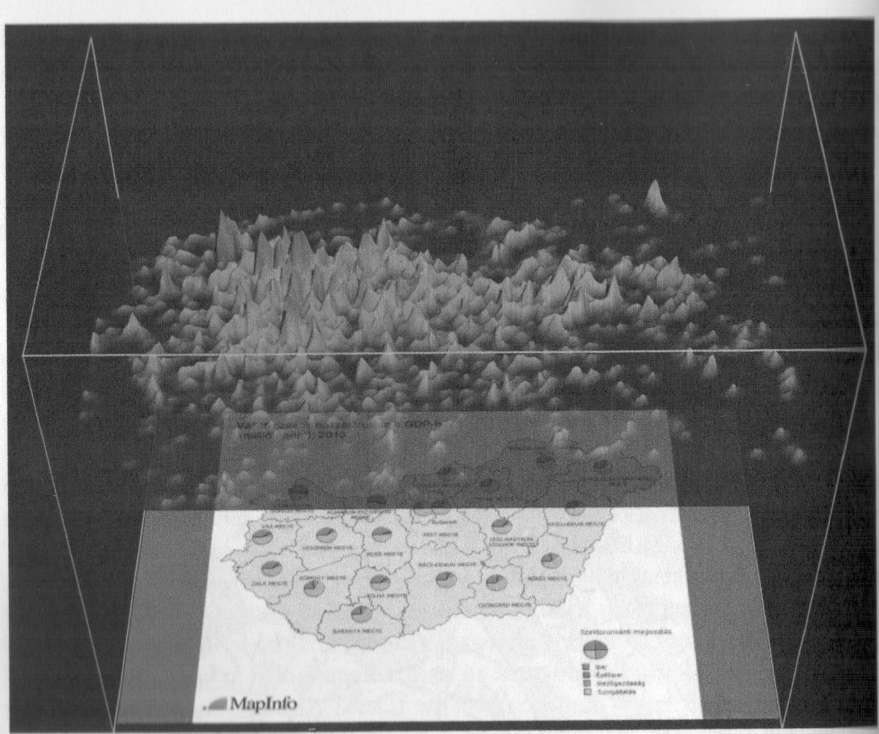


Fig. 3.11 Eyetracking data visualized in three dimensions by Török and Bérces [28]

practical experience gained in the planning of three dimensional rendering softwares is already valuable for other areas, where three dimensional visualization has just begun to emerge (Fig. 3.11).

The other field where three dimensional visualization is already widespread is medical imaging. Medical imaging techniques such as computer tomography (CT), structural and functional magnetic resonance imaging (sMRI and fMRI), and magnetoencephalography (MEG), along with other methods, are available in medical practice for decades. The ultimate aim of these tools to help diagnosis by providing spatial information of lesions or other alterations of tissue. These images are not only used to describe the medical situation but also to prescribe surgery. For example, pharmacologically intractable epilepsy patients undergo surgery based on the MRI + ECoG localization of epileptic foci [62]. Since in these situations millimeters of mislocalization means potential harm to well-functioning brain tissue, the visualization of MR images is of great importance. Medical doctors have been using softwares like SPM [63] to analyze and visualize magnetic resonance imaging data. While these tools are excellent in correcting artifacts and reconstructing image from the original frequency domain information (see more in [64]), they are generally not outstanding when it comes to visualization. Luckily, in recent years more and more tools became available for medical staff to utilize virtual reality to visualize medical

images [65]. Visualizing tissues and organs in three dimensions not only lets the viewer to freely observe the surroundings of the given locus, but these views can be easily collaboratively shared with other practitioners. Nevertheless, the spread of mixed reality is still limited by the some factors. First, while head mounted displays are available on the consumer market medical doctors may utilize more augmented interfaces, which can be more easily used for collaboration [66]. Of course, virtual reality and realistic models are not only used for diagnosis but also for teaching and practicing purposes [67–69].

3.4.5 *Using Non-Euclidean Spaces*

The reason why three dimensional visualization easily spreads in engineering design and medical imaging is that in both cases the actual data of which we are gaining insight is three dimensional. Therefore, using three dimensions for the representation means no significant spatial information loss. Unfortunately, this is not true for higher dimensional problems. Take, for example, a graph created from the co-occurrence matrix of a paper (see Fig. 3.12). The dimensionality of a graph is the least n such that there exists a representation of the graph in the Euclidean space of n dimensions where the vertices are not overlapping and edges are of unit length [71]. This number can easily go very high as the number of edges increase, actually the upper limit of n for graph G is twice its maximal degree plus one [72]. Because of this (and also because of the computational complexity of identifying dimensionality) common graph representations often use not unit length edges. For example, a widespread graph representation—the spring layout—uses physical simulations by assigning forces to edges and their endpoint nodes. This way the resulting layout shows more interconnected regions being closer and less connected vertices are pulled to the extremities of the available space (see also on Fig. 18.2). In these kinds of representations—since the actual physical position of a vertex is not meaningful without the connected vertices—two dimensional embedding of the layout is usually preferred since adding a third dimension would only add another item to the arbitrary position vector.

However, information that may not easily be represented in Euclidean space can still easily be processed by the human brain. The simplest example for this is our social network of friends. If we need to visualize the relationship even just a cluster of our friends we will be in trouble: the information does not fit easily to the two dimensional paper or a three dimensional virtual space. Nevertheless, we can easily 'navigate' between these people because our cognitive map does not need to conform necessarily the norms of the Euclidean space. This means we can conveniently utilize walls/borders, routes, shortcuts, and even subspaces. Shortcuts are probably the most interesting of these since they not even need to be physically possible shortcuts. Studies show that people easily learn to navigate in space with teleportation wormholes [70, 73, 74]. The fact that these can be processed means also that we can design environments where we purposefully place such things. That is we can

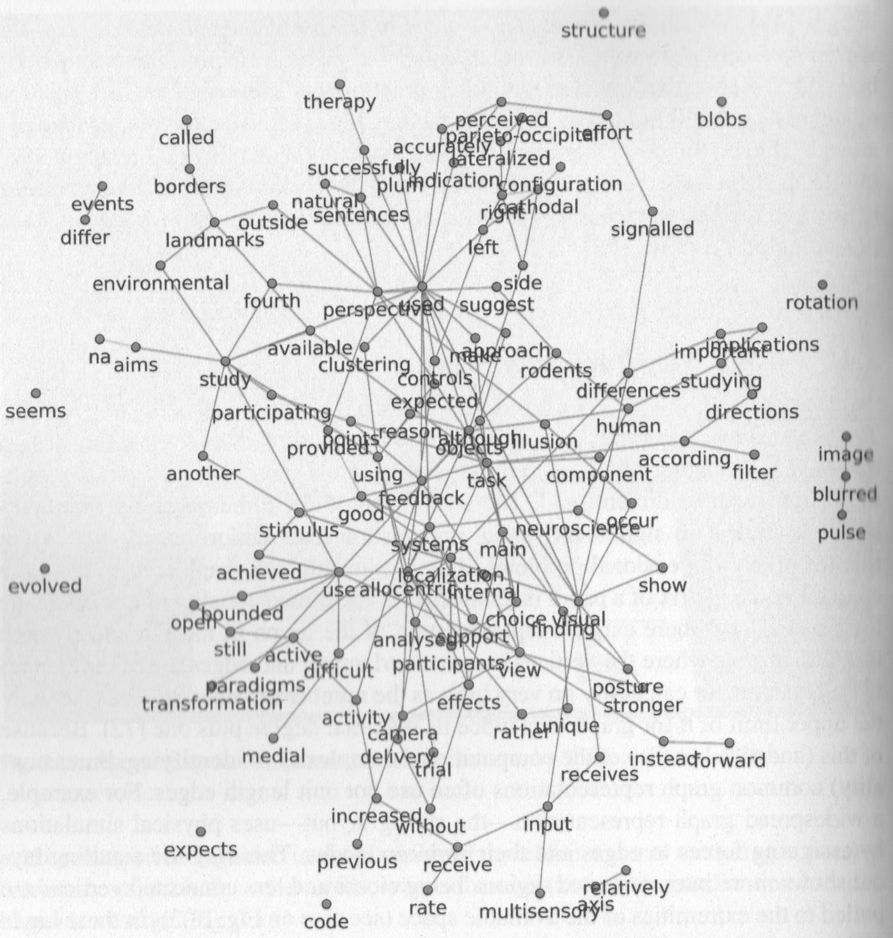


Fig. 3.12 A graph created from the bigrams mined in one previous work [70] of one author of the current review. For presentation purposes only a randomly chosen fraction of the nodes and edges are displayed

visualize graphs like impossible yet interpret figures by defining such shortcuts [6]. Similar, artificial memory spaces have been used by ancient Greeks and other cultures to store large amount of information in memory, also known as the '*method of loci*' [75].

Interestingly, these graphic tools differ from those ones we consider conventionally as visualizations in one key factor, which is perspective. While traditional visualizations are viewed from an external perspective, the above mentioned mental visualizations are viewed from an embedded perspective. The difference between these two perspectives is even more pronounced in the brain. Embedded perspective is associated with egocentric reference frame use, while external perspective is

associated with allocentric reference frame use [76]. Furthermore, there are two core geometric systems in the brain. One is responsible for analyzing two dimensional forms from an external perspective (e.g. studying a map) and the other is responsible for navigating three dimensional environments from an internal viewpoint (e.g. actual navigation). Studies have found that neither of these two core geometric systems is able to represent correctly all of the fundamental properties of Euclidean geometry, which are distance, angle and directional relationships [77]. Studies showed that from the external perspective length/distance and angle information are correctly identified but shapes are easily mistaken for their mirrored versions. In turn, during navigation length information and direction are parsed easily, but angles are not well remembered. Therefore, changing the perspective in visualization is not only a matter of aesthetics, but requires a cognitive reframing of information.

There are also drawbacks of the non-Euclidean properties of the cognitive map for the representation of three dimensional information. Unlike teleportation, three dimensional rotational movements are proven to be difficult for humans [78]. This is not surprising since spatial perception is essentially a multisensory process where the vertical axis remains the most basic spatial knowledge for humans [34], even if views can be visually similar in any direction. In fact, representation of three dimensional space has only been verified in bats [79, 80]. Bats are flying animals, and they use echolocation as their primary distal sensory system. Importantly, the activity of the hippocampal formation in bats does not exhibit oscillatory activity in the theta band, which, in turn, is an essential functional correlate in both rodents and humans [80]. Therefore, the spatial representation in bats is different from that in rats [81] and presumably from that in humans, too. Thus, although some nervous systems have developed to deal with three dimensional navigation, the human brain has not.

3.4.6 *The Niche for Interactive Visualizations*

Most researchers would agree that, although dynamic and interactive visualizations may look impressive, they are often not more than useless 'eye-candy'. Many open source (plot.ly, shiny) and proprietary projects (Microsoft PowerBI, Tableau) offer solutions for more interactive visualization, so it may become even more widespread in the near future. In the current section we introduce some examples where dynamic visualizations are favored over static ones, and they can facilitate the better communication of insights.

With dynamic and interactive visualizations authors have to communicate information in a generally interesting way to call users' attention. For example, when someone wants to tell how house renting and buying expenses are related, he or she may need to use several separate graphs to display the factors contributing to costs and proceeds. This kind of visualization is easily skipped by most viewers since the information conveyed—despite being relevant—is too complex. However, if the authors can tailor the message for the actual viewer it will reach its goal easily. This was what Bostock et al. [82] did in their interactive visualizations published in the on-line edition of The New York Times. Here the reader is invited to adjust sliders on the specific factors to reach a conclusion at the end if renting or buying pays off for his/her *specific* case. Therefore, interactive visualization is sometimes useful: when understanding the structure in high dimensional data would require large effort from the reader's side. It can help increasing the incentive value of the visualization and motivate readers to engage in the understanding of the image. Nevertheless, this also means that not the exact same message will be delivered to each reader, thus the variance in the message has to be considered when designing the visualization and interpretations.

In sum, mixed reality brought visualization new challenges. The ability to visualize data in three physical dimensions is sometimes useful (e.g. medical diagnostics), but oftentimes does not contribute to better understanding. However, mixed reality is not only capable of visualizing data in three dimensions but makes us able to place or project a visualization anywhere, not only on computer screens. Embedded and situated visualizations could be easier to understand since the surrounding environment could provide us fundamental context for the interpretation. These visualizations will quickly become widespread—as soon as affordable augmented reality headsets are entering the consumer market [83].

Nevertheless, especially with embedded visualizations one has always to consider that, although visual modality plays a pivotal role in human perception, the process is still affected by other sensory modalities as well, e.g. the vestibular system. Finally, mixed reality can help us to visualize structures that are hard to understand in pictures, but these relations are readily processed once the perspective is not out of the visualization but is internal. Good examples are graphs and other high dimensional structures that are visualized in non-Euclidean ways.

3.5 Summary

Cognitive data visualization is a novel approach to data visualization focusing on the strengths and weaknesses of the human mind in knowledge acquisition. Especially in cases beyond the capacity of human senses our working memory we rely upon external memory tools as projections of the human mind. The graphic representation, mapping in its most general sense, creates spaces of data and information which are open to visual and mental exploration and navigation. As a process analogue to similar activities in real world, physical or geographical spaces, visualization is inherently a visuospatial process resulting in the recognition of relations, patterns or structures in images.

Data visualization has a long history starting with the first spatial representations in ancient times. After the pioneer thematic maps in the early modern age systematic data collection increased in the Enlightenment period, and resulted in new forms of visual knowledge. Graphic data representation methods developed rapidly in the 19th century, when the traditional graphical methods were practically all invented and tested in a great variety, in masses of statistical graphs, diagrams and thematic

maps produced and distributed in all societies around the world. Visualization tools were reproduced by lithographic and offset printing and became common not only scientific research but also in popular culture. A good example of this development is the appearance of isothermal charts in school atlases which laid the foundations of the recent popularity of heatmaps. By the 1980 s, when visualization became computer graphics, the traditional methods were so deeply integrated in modern culture that their effectivity was rarely questioned. Only in the new millennium, when new visualization methods in new environments (e.g. virtual and augmented reality, network spaces and big data etc.) became more and more important in human computer interaction, became cognitive issues of data visualization seriously considered.

As it is apparent from recent research issues *visualization have vital importance in future human-computer interaction (HCI)*, where the rapid development of artificial intelligence urgently requires more effective interfaces than the obsolete existing ones. Here plays the human visual mind a key role: with new visualizations developed on empirical research on human cognitive processes the interaction with information and spaces, interactively generated by AI, can be more effective. Based on neuropsychological research findings *cognitive design* can already effectively influence pre-attentive visual processes. However, as we emphasize here, human vision is a product of both *biological and cultural* evolution. Modern researchers can not only learn from the empirical knowledge cumulated by traditional methods, but it is necessary to better know the cultural traditions and history of visualization.

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