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Information Visualization

Dr. rer. nat. Dipl. Inform. Michael Burch

Abstract Visualization in general and Information Visualization in particular are growing disciplines that have the common goal to generate in this order readable, understandable, intuitive, and aesthetically looking pictures from a given dataset. Information Visualization (InfoVis) typically deals with abstract, discrete, and non-spatial data, i.e. data that has no inherent spatial structure, for example relational data as it is given by social networks or text data in Twitter messages. In contrast, Scientific Visualization (SciVis) deals with continuous and spatial data, i.e. data that has an inherent spatial structure, for example MRI (Magnetic Resonance Imaging) scans or fluid dynamics data. The invention of the computer allows us to quickly produce visualizations of large datasets. As another benefit, we are able to let awake the generated diagrams to life by allowing the integration of interactive features and to play around with huge datasets of an abstract nature. The major goal of Information Visualization is to make vast amounts of data understandable for an analyst in a very short time and to uncover many insights that he would never find without using a visual encoding of such abstract data. In this lecture I will demonstrate the benefits of the field of Information Visualization by means of many application examples coming from various application domains dealing with different types of data but I will also show the limitations that visualizations have. The deciding role for an efficient and effective diagram definitely plays the applied visual metaphor that has to be found by the visualization designer. This visual metaphor is exactly the point that gives a researcher in Information Visualization some degree of freedom when designing a novel visualization technique. For finding out if the visual metaphor in use is the one that performs best with respect to a given task and if the design of the technique is appropriate we have to record user performances in a comparative user study which also shows up as a challenging task. Many of the described visualization techniques are illustrated by means of pseudo code and also as runnable source code given in the JAVA programming language.

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1 Introduction

Visualization techniques already existed long before the invention of the computer. Ever since humans were producing visual depictions of processes surrounding them. Early forms of cave paintings illustrate how people already made things visual several thousand years ago. In the 19th century much data (for these days) has been collected on paper that was already too large to extract insights without a picture of it in mind. With the advent of the computer age people were able to quickly and automatically produce interactive diagrams, charts, plots, or infographics from such datasets but the progress in hardware and software technology did not only lead to a faster data processing but also to a data explosion meaning a new challenge for visualization researchers.

1.1 Motivating Example

We are confronted by the following scenario. We are given a list of value pairs from which we know that they encode \((x, y)\)-coordinates, i.e. a textual representation of data maybe stored electronically or just written down with pencil and paper. We are reading the data and we are trying to understand it, to derive some meaning. But the task of obtaining insight in the data and to uncover the hidden message is very difficult when not even impossible, see Table 1. This table shows a sequence of \((x, y)\)-coordinates numbered from 1 to 5. The only thing that we know about the data is the order in which the \((x, y)\)-coordinates appear and their exact values. For understanding the data rapidly we need some kind of visual mapping, i.e. a function that maps each data point to a graphical primitive and also possible relations between those data points. The single data points in our example are given by the \((x, y)\)-coordinates and also a relation between the data points exists—the sequential order as given by the list.

Table 1 A sequence of \((x, y)\)-coordinates: Just inspecting the textual representation of the data can hardly be used to explore it for patterns or derive some meaning in order to detect hidden messages in it.

<table>
<thead>
<tr>
<th>Number</th>
<th>(x)</th>
<th>(y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>55</td>
<td>237</td>
</tr>
<tr>
<td>2</td>
<td>197</td>
<td>237</td>
</tr>
<tr>
<td>3</td>
<td>242</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>126</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>100</td>
</tr>
</tbody>
</table>

Now, we get a simple but powerful idea. We transform the textual representation of the data into a visual one by drawing the \((x, y)\)-coordinates to their respective positions on either the two-dimensional screen or by a pencil to a sheet of paper by
placing a black dot to each of the respective positions, see Figure 1. The sequential order of the points, i.e. the relations, is visually encoded by straight lines connecting subsequent points in the list.

The black dot is the visual encoding for a data point (which is not required anymore because the line connections show them implicitly, see Figure 1), the straight line represents the visual encoding of the relation between two subsequent points. Such a visual encoding is sometimes also called the visual mapping or also a visual metaphor expressing nothing more than the function that takes data as input and that outputs a corresponding visualization. The visual metaphor describes from which general type a specific visual encoding is derived, i.e. a visual metaphor is the common form in which many subtypes can be categorized in, all having similar characteristics. This mapping plays a crucial role in Information Visualization. It requires some kind of creativity for the researcher working in the field of Information Visualization. The visual mapping must be applied in a way to be easily understandable, readable, and intuitive but on the other hand it should also be nice looking, i.e. aesthetically appealing, if possible.

Figure 1 shows a regular pentagon which was not visible by just inspecting the five \((x, y)\)-coordinates in their textual form. When inspecting them for a long time in order to derive some meaning we find ourselves creating visual depictions of it in our mind. This is how we build our mental image of the data. In this small dataset scenario it might be a good strategy to understand what is going on between this handful of data points but nowadays we have to deal with big data which cannot be explored with the same concept. Consequently, a computer-driven solution is needed which works fast and reliably. But also such a computer-based visualization is strongly dependent on the visual metaphor to be applied.

**Definition 1.1.1 (Visual Metaphor):** A visual metaphor can be understood as a mapping of data to a visual concept where the data points are represented as graph-
ical primitives. A visual metaphor is based on familiar symbols in order to make it understandable. It represents some kind of analogy to something well-known from another field.

In the figure we can now see the collection of points drawn to the two-dimensional plane. Our visual system is now able to derive some meaning from the collection of points. To understand this visualization we make use of concepts from a theory that goes back to early work of Max Wertheimer [22] known as Gestalt theory - humans are able to see a figure in its entirety instead of combined of its single parts. This means we do not see the single points but we directly derive an entire figure with some meaning, here the regular pentagon pattern in Figure 1. How we interpret the resulting visualization composed of the points and lines strongly depends on what we have already seen, experienced, and remembered in our life.

1.1.1 Exercises

1. You are standing on a motorway bridge armed with pencil and paper in your hand. You write down the timestamp, the brand, and the color of all the cars that are passing the bridge for 24 hours. How can you use visualization to find interesting patterns in that kind of recorded data?

2. Can you imagine any problems that might occur when recording the data and when visualizing it?

1.2 Definitions and Origin

Visualization in general and Information Visualization in particular are disciplines that live from creativity. It is up to you - the visualization creator and designer - to either use existing visual metaphors or break free and try something totally new. Inspecting the things from a different perspective or from a different point of view may sometimes be the key idea to find novel visualization techniques that may be further enhanced and that may be used one day from a broad population such as inventions like metro maps or bar charts which ease our daily life. Checking if they really perform better than existing ones is the key idea of comparative user studies that will also be in focus of this lecture.

I would like to start with a famous quote:

"A picture is worth a thousand words"

meaning that when we see a picture we are able to perceive and understand very complex phenomena in a very fast and reliable way, see Figure 2. I do not have to explain this figure because it is self-explanatory. When looking at the textual
description on the right it takes more time to read it and it might be interpreted differently by each viewer.

![A Picture is worth a thousand words.](image)

**Fig. 2** A picture is worth a thousand words.

In some scenarios we also speak out:

"Now I can see what you mean."

This shows that we also think visually. We form a mental image of that what is communicated among us in a conversation for example. Sitting in a pub and discussing the soccer match from last evening leads to a mental and visual revival of the scenes during the match when talking about it. This means in many cases it seems as if we store the data already in a visual form in our minds. This is another benefit of visualization. Not only are we able to faster understand visually represented data but we can also store a visualized dataset much better, i.e. the patterns occurring in it. These facts make visualization techniques a needed concept to efficiently and effectively communicate data to ourselves and also from person to person, i.e. to a broader audience.

There are many definitions for the term visualization as well as Information Visualization.

**Definition 1.2.1 (to visualize):** As given in the American Heritage Dictionary of the English Language, the verb 'to visualize' means (see Figure 3):

1. To form a mental image of; envisage: tried to visualize the scene as it was described
2. To make visible

In the following we will restate some definitions for the term visualization as used by researchers working in the field.
The very first definition for the term visualization was given in an NSF Panel in 1987 by McCormick, DeFanti, and Brown [15]:

'Visualization is a method of computing. It transforms the symbolic into the geometric, enabling researchers to observe their simulations and computations. Visualization offers a method for seeing the unseen. ... It studies those mechanisms in humans and computers which allow them in concert to perceive, use and communicate visual information.'

A more detailed description about this very first meeting is given on a corresponding website:

'In October 1986, the Division of Advanced Scientific Computing (DASC) of the National Science Foundation (NSF) sponsored a meeting of a newly-organized Panel on Graphics, Image Processing and Workstations to provide input to DASC on establishing and ordering priorities for acquiring graphics and image processing hardware and software at research institutions doing advanced scientific computing, with particular attention to NSF-funded supercomputer centers. Supercomputer centers had been requesting funds to provide graphics hardware and software to scientific users but, in point of fact, existing tools were not adequate to meeting their needs.

Computer graphics and image processing are within computer science; the application of computers to the discipline sciences is called computational science. Applying graphics and imaging techniques to computational science is a while new area of endeavor, which Panel members termed Visualization in Scientific Computing.

The Panel maintained that visualization in scientific computing is a major emerging computer-based technology warranting significantly enhanced federal support. From the Panel’s first meeting came two principal recommendations. It was suggested that the NSF hold a workshop with other government agencies in order to generate a formal summary of the field, and that the NSF establishes a new initiative on Visualization in Scientific Computer (ViSC).
The Workshop on Visualization in Scientific Computing, held February 9-10, 1987 in Washington, D.C., and co-chaired by Panel members Bruce H. McCormick and Thomas A. DeFanti, brought together researchers from academia, industry and government. Computer graphics and computer vision experts analyzed emerging technologies, and federal agency representatives presented their needs and interests. Scientists showed examples of their computer-generated imagery using film, videotape and slides. A presentation on Japanese visualization research, a tutorial on state-of-the-art computer graphics animation research, and an overview of commercially available hardware and software rounded out the agenda.

This report presents the findings and recommendations of the Panel for a new initiative in Visualization in Scientific Computing. Much of the impact of visualization, as applied to scientific and engineering research, cannot be conveyed in printed matter alone - so this document is accompanied by a videotape that illustrates pioneering efforts in visualization today.

Today, many different definitions for the term visualization or information visualization exist that all have similar meanings by expressing it in a slightly different manner. Here are some of an endless list which seem to meet the point best:

- The use of computer-supported, interactive, visual representations of abstract data to amplify cognition [2].
- Both scientific visualization and information visualization create graphical models and visual representations from data that support direct user interaction for exploring and acquiring insight into useful information embedded in the underlying data [16].
- Information visualizations attempt to efficiently map data variables onto visual dimensions in order to create graphic representations [6].
- Information Visualization (InfoVis) is the communication of abstract data through the use of interactive visual interfaces [11].
- Information Visualization utilizes computer graphics and interaction to assist humans in solving problems [17].
- Information Visualization is a set of technologies that use visual computing to amplify human cognition with abstract information [1].
- Information visualization promises to help us speed our understanding and action in a world of increasing information volumes [1].
- The purpose of information visualization is to amplify cognitive performance, not just to create interesting pictures. Information visualizations should do for the mind what automobiles do for the feet [1].

Over the years the field of visualization split into several subareas such as Software Visualization, Graph Drawing and Graph Visualization, BioVisualization, GeoVisualization, Scientific Visualization, or Information Visualization to mention the most important ones. Figures 4 (a) - (f) illustrate typical visualization examples in each of the fields.
How to define the difference between them depends on the data they try to visualize and the methods and techniques in use. For example, it is said that Scientific Visualization (SciVis) deals with continuous and spatial data, i.e. data that has an
inherent spatial structure, for example MRI (Magnetic Resonance Imaging) scans or fluid dynamics data. In contrast, Information Visualization (InfoVis) typically deals with abstract, discrete, and non-spatial data, i.e. data that has no inherent spatial structure, for example relational data as it is given by social networks or text data in Twitter messages, see Figure 5.

![Diagram](image)

**Fig. 5** The difference between Scientific Visualization and Information Visualization based on the data they visually encode [20].

### 1.2.1 Exercises

1. Try to find visualizations in your everyday life that best meet the quote ‘A picture is worth a thousand words.’
2. Can you also find bad examples for visual depictions of data? Why do you think they are not useful and how might they be improved/redesigned?

### 1.3 Early Forms of Visualization

Going very many years back in time, we can find early forms of visual depictions on cave walls and ceilings. Those are of prehistoric origin. The earliest such rock art in Europe dates back to the Aurignacian period, approximately 40,000 years ago, and is found in the El Castillo cave in Cantabria, Spain [4], see Figure 6. The exact purpose of the paleolithic cave paintings is not known. Evidence suggests that they were not merely decorations of living areas, since the caves in which they have been
found do not have signs of ongoing habitation. They are also often located in areas of caves that are not easily accessible. Some theories hold that cave paintings may have been a way of communicating with others, while other theories ascribe them a religious or ceremonial purpose.

![Cave painting](image)

**Fig. 6** Cave of Altamira known as the Sistine Chapel of the cave painting, near Santander, Spain.

There are many examples for cave paintings which means that those have not been designed by accident. People all over the world produced this kind of art focusing on visually encoding impressions from their life, see for example Figures 7 (a) - (i).

The most common themes in cave paintings are large wild animals, such as bisons, horses, aurochs, and deer, and tracings of human hands as well as abstract patterns, called finger flutings. The species found most often were suitable for hunting by humans, but were not necessarily the actual typical prey found in associated deposits of bones; for example, the painters of Lascaux have mainly left reindeer bones, but this species does not appear at all in the cave paintings, where equine species are the most common. Drawings of humans were rare and are usually schematic as opposed to the more detailed and naturalistic images of animal subjects. One explanation for this may be that realistically painting the human form was "forbidden by a powerful religious taboo."

Pigments used include red and yellow ochre, hematite, manganese oxide and charcoal. Sometimes the silhouette of the animal was incised in the rock first, and in
some caves all or many of the images are only engraved in this fashion, taking them somewhat out of a strict definition of "cave painting".

Similarly, large animals are also the most common subjects in the many small carved and engraved bone or ivory (less often stone) pieces dating from the same periods. But these include the group of Venus figurines, which have no real equivalent in cave paintings.

Henri Breuil interpreted the paintings as being hunting magic, meant to increase the number of animals. Another theory, developed by David Lewis-Williams and broadly based on ethnographic studies of contemporary hunter-gatherer societies, is that the paintings were made by paleolithic shamans. The shaman would retreat into the darkness of the caves, enter into a trance state and then paint images of their visions, perhaps with some notion of drawing power out of the cave walls themselves.

R. Dale Guthrie, who has studied both highly artistic and publicized paintings and a variety of lower quality art and figurines, identifies a wide range of skill and ages among the artists. He hypothesizes that the main themes in the paintings and other artifacts (powerful beasts, risky hunting scenes and the representation of women in the Venus figurines) are the fantasies of adolescent males, who constituted a large part of the human population at the time. However, in analysing hand prints and stencils in French and Spanish caves, Dean Snow of Pennsylvania State University has proposed that a proportion of them, including those around the spotted horses in Pech Merle, were of female hands.
1.3.1 Exercises

1. Use Google Image Search to find Cave Paintings and try to interpret them by just inspecting the picture!
2. Are there any commonalities with respect to the visualized scenes, applied color codings, or used graphical primitives among them?

1.4 Visualization before the Invention of the Computer

In the years before the invention of the computer people were also able to design and produce visualizations. These were drawn by hand and were static depictions of small datasets, i.e. interactive features as these are understood today were not applicable in order to navigate in the data or have a look at it from different linked perspectives. For sure, one might argue that we can also interact with a visualization drawn on a piece of paper by rotating the paper or looking closer and further apart but this is not meant by interaction in the broad sense of modern information visualization.

There are several good examples of graphical representations of data from this time. One might also argue that those old visualizations are not useful anymore today and cannot keep up with the steadily growing datasets but the general concepts are sometimes also used today and can be seen everywhere.

Harry Beck

One of those visualization examples is the diagram invented by Harry Beck (4 June 1902 - 18 September 1974), who was an English engineering draftsman. He is known for having created the London Underground Tube map in 1931.

Beck drew up the diagram in his spare time while working as an engineering draftsman at the London Underground Signals Office. London Underground was initially sceptical of Beck’s radical proposal, an uncommissioned spare-time project, but tentatively introduced it to the public via a small pamphlet in 1933. It was immediately popular, and the Underground has used topological maps to illustrate the network ever since, see Figure 8.

Prior to the Beck diagram, the various underground lines had been laid out geographically, often superimposed over the roadway of a city map. This meant the centrally located stations were shown very close together and the out-of-town stations spaced far apart.

It was clearly Beck who had the idea of creating a full system map in colour though. He believed that passengers riding the Underground were not too bothered about geographical accuracy, and were more interested in how to get from one station to another and where to change trains. "It does not matter where you are when you are underground", Beck argued.
Thus Beck drew his famous diagram, which looked more like and indeed was based upon the concept of an electrical schematic than a true map, on which all the stations were more-or-less equally spaced. Beck first submitted his idea to Frank Pick of London Underground in 1931, but it was considered too radical because it didn’t show distances relative from any one station to the others. The design was therefore rejected by the Publicity department at first, but the designer persisted. So, after a successful trial of 500 copies in 1932, distributed via a select few stations, the map was given its first full publication in 1933 (700,000 copies). The positive reaction from customers proved it was a sound design, and a large reprint was required after only one month.

**John Snow**

Another scenario where visualization really helped to understand a dataset in order to solve an occurring medical problem is given by John Snow.

John Snow (1813-1858), the ‘godfather of epidemiology’, was born in York, where his father worked in the local coal yards. He was a doctor of medicine, apprenticed at one time to the physician to George Stephenson and his family.

He is renowned for his ‘spot map’ (an early form of geospatial mapping) showing the deaths from cholera during the 1854 outbreak in Soho, superimposed on a map of the area around Broad Street (Figure 9). This led to the source of the outbreak being traced to the Broad Street water pump (the well for which, it subsequently transpired, had been dug only three feet from an old cesspit). Snow thus established
that cholera was a waterborne disease - and not, as was then believed, caused by vapours or 'miasma'. The pump handle was subsequently removed on 8th September, 1854 - an event which is symbolically re-enacted every September by the John Snow Society, following the annual Pumphandle Lecture. The site of the original pump can be found just outside the John Snow public house in Broadwick Street. Snow died of a stroke at the age of 45, and is buried in Brompton Cemetery.

Florence Nightingale

Somewhat related to this example is the visualization of Florence Nightingale (1820-1910), named after the Italian city in which she was born. She is well known for her nursing exploits during the Crimean war. She was also a formidable social reformer and statistician, and the first woman (in 1858) to be elected Fellow of the Statistical Society of London (the forerunner of the present day Royal Statistical Society). Her 'coxcomb' or 'wedge' charts (Figure 10) demonstrated dramatically
that far more deaths in British soldiers in the Crimea were caused by infections and preventable diseases than by wounds, and she successfully lobbied for improved sanitation in military hospitals - thereby greatly reducing the death rate.

Fig. 10  The ‘coxcombs’ or ‘wedge’ charts invented by Florence Nightingale. These are also called Polar-Area diagrams.

She set up the Nightingale Training School at St. Thomas’ Hospital on 9 July 1860. Now known as the Florence Nightingale School of Nursing and Midwifery, this is part of King’s College London. During the 1870s she supported the idea of instituting a medal for achievement in statistics, in memory of Adolphe Quetelet, and in the early 1890s she and Francis Galton (see below) formulated plans for a new Chair of Applied Statistics at Oxford. Sadly, the proposals came to nothing. In 1883, Nightingale was awarded the Red Cross by Queen Victoria, and in 1907 she became the first woman to be awarded the Order of Merit.

On 13 August 1910, at the age of 90, she died peacefully in her sleep in her room at 10 South Street, Park Lane. The offer of burial in Westminster Abbey was declined by her relatives, and she is buried in the graveyard of St. Margaret’s Church in East Wellow, Hampshire.

Charles Joseph Minard

Another very popular example of an early depiction of data is the so called Minard Map. Charles Joseph Minard (1781-1870) was an engineer and cartographer, born in Dijon, France. His 1869 ‘Carte Figurative’ (Figure 11), depicting the utter destruction of Napoleon’s Grande Armee during his Russian campaign of 1812/13, is arguably the most poignant graph ever produced. It combines many elements, show-
ing the physical route of the army in its advance on, and retreat from, Moscow, the location of the army at certain dates, and the temperatures encountered on the retreat. The size of the army is indicated by the width of the coloured zones (gold for advance, black for retreat), on a scale of 1 mm for 10,000 men. The corresponding numbers of men are shown at various points along the route. Thus we see an army of 422,000 men setting out on the grand enterprise. A fraction of the troops can be seen splitting off from the main army and pausing at Polotzk. These troops remained relatively undiminished, and rejoined the remnants of the main army in their retreat. By the time Napoleon reached Moscow, his troop numbers were reduced to 100,000 (still a formidable force), but he found little worth conquering - Czar Alexander I and the residents of Moscow had fled, burning the city behind them. Napoleon had little choice but to retrace his steps through the bleak Russian winter. As shown on the graph, the temperature fell as low as -30 degrees Celsius on 6th October, 1812. Only 10,000 of the original 422,000 survived. As with Florence Nightingale’s soldiers, the majority had died from cold, hunger and disease - not from wounds or enemy action.

![Fig. 11](image)

**Fig. 11** A map by Charles Joseph Minard showing the march of Napoleon’s army during his Russian campaign of 1812/13.

Although Minard includes a description above his chart, it is almost completely unnecessary. All the pertinent information is readily apparent from a close examination of the chart itself. Minard was a master at the production of maps such as these that combined tremendous amounts of data with geographic representations. Edward Tufte, an expert in the visual display of quantitative information, has called this chart "probably the best statistical graphic ever drawn."

Although the most striking feature of the chart is the thinning line of soldiers, the map in the background plays an important role, showing the cities and rivers the army traversed on its way into and out of Russia. This chart demonstrates how, with good planning a design, maps can operate in concert with many other types of information to create stunning displays of information.
A companion, though less dramatic, graph (see Figure 12) shows the depredations suffered by Hannibal’s troops as he marched on Rome during the Second Punic War. The loss of life entailed in his famous crossing of the Alps (despite his elephants) is immediately evident.

Minard’s map charts Hannibal’s path from Iberia (Spain), across southern Gaul (France), across the Alps and into Italy. Minard represents the number of men in Hannibal’s army with the thickness of the line showing the army’s path. One millimeter of thickness represents 1,000 men. The Hannibal map, however, is not as striking as the Napoleon map. For one, the numbers of men involved in Hannibal’s invasion are significantly smaller. Minard could have exaggerated Hannibal’s losses by increasing the ratio of men to line thickness, but held exactness in too high - a regard to attempt such data manipulation.

As Minard’s obituarist notes, his famous graph ‘inspires bitter reflections on the cost to humanity of the madnesses of conquerors and the merciless thirst of military glory’.

**William Playfair**

William Playfair (22 September 1759 - 11 February 1823) was a Scottish engineer and political economist, the founder of graphical methods of statistics.

William Playfair invented four types of diagrams: in 1786 the line graph (see Figure 13) and bar chart (see Figure 14) of economic data, and in 1801 the pie chart (see Figure 15) and circle graph, used to show part-whole relations.

Playfair was born in 1759 in Scotland during the Enlightenment, a Golden Age in the arts, sciences, industry and commerce. He was the fourth son of the reverend James Playfair of the parish of Liff and Benvie near the city of Dundee in Scotland. His notable brothers were architect James Playfair and mathematician John Playfair. His father died in 1772 when William was 13, leaving the eldest brother John to care
Fig. 13 Playfair’s trade-balance time-series chart, published in his Commercial and Political Atlas, 1786.

Fig. 14 In this bar chart Scotland’s imports and exports from and to 17 countries in 1781 are represented.

for the family and his education. After his apprenticeship with Andrew Meikle, the inventor of the threshing machine, he became draftsman and personal assistant.

Playfair had a variety of careers. He was in turn a millwright, engineer, draftsman, accountant, inventor, silversmith, merchant, investment broker, economist, statisti-
ian, pamphleteer, translator, publicist, land speculator, convict, banker, ardent royalist, editor, blackmailer and journalist. On leaving Watt’s company in 1782, he set up a silversmithing business and shop in London, which failed. In 1787 he moved to Paris, taking part in the storming of the Bastille two years later. He returned to London in 1793, where he opened a “security bank”, which also failed. From 1775 he worked as a writer and pamphleteer and did some engineering work.

Ian Spence and Howard Wainer in 2001 describe Playfair as “engineer, political economist and scoundrel” while “Eminent Scotsmen” calls him an “ingenious mechanic and miscellaneous writer.” It compares his career with the glorious one of his older brother John Playfair, the distinguished Edinburgh professor, and draws a moral about the importance of “steadiness and consistency of plan” as well as of “genius.”

Two decades before Playfair’s first achievements, in 1765 Joseph Priestley had created the innovation of the first timeline charts, in which individual bars were used to visualize the life span of a person, and the whole can be used to compare the life spans of multiple persons. According to Beniger and Robyn (1978) “Priestley’s timelines proved a commercial success and a popular sensation, and went through dozens of editions”. These timelines directly inspired William Playfair’s invention of the bar chart, which first appeared in his Commercial and Political Atlas, published in 1786. According to Beniger and Robyn (1978) “Playfair was driven to this invention by a lack of data. In his Atlas he had collected a series of 34 plates about the import and export from different countries over the years, which he presented as line graphs or surface charts: line graphs shaded or tinted between abscissa and function.
Because Playfair lacked the necessary series data for Scotland, he graphed its trade data for a single year as a series of 34 bars, one for each of 17 trading partners”.

In this bar chart Scotland’s imports and exports from and to 17 countries in 1781 are represented. “This bar chart was the first quantitative graphical form that did not locate data either in space, as had coordinates and tables, or time, as had Priestley’s timelines. It constitutes a pure solution to the problem of discrete quantitative comparison”.

Playfair, who argued that charts communicated better than tables of data, has been credited with inventing the line, bar, and pie charts. His time-series plots are still presented as models of clarity.

Playfair first published The Commercial and Political Atlas in London in 1786. It contained 43 time-series plots and one bar chart, a form apparently introduced in this work. It has been described as the first major work to contain statistical graphs. Playfair’s Statistical Breviary, published in London in 1801, contains what is generally credited as the first pie chart.

**Francis Galton**

Francis Galton (1822-1911) - scientist, statistician and African explorer - was a cousin of Charles Darwin. He was born in Birmingham, the youngest of eight children of a prominent Quaker family. He studied medicine at King’s College London and mathematics at Cambridge. He was a man of diverse talents, and was responsible (amongst many other projects) for the first weather map, a theory of anticyclones, and the system for classifying fingerprints still in use today. He wrote a treatise on how to make the perfect cup of tea, and published a ‘beauty map’ of the British Isles - based on the number of attractive women he encountered on his travels. (London came out with the highest score; Aberdeen the lowest.)

Among his many statistical achievements, he is credited with the introduction of the standard deviation, the correlation coefficient and the regression line. His discovery of the phenomenon of ‘regression to the mean’ is illustrated in his famous chart (Figure 16) shown at the Royal Institution Lecture of 1877. Among his proteges was the great statistician Karl Pearson. He was knighted in 1909.

Perhaps unfortunately, Galton is best remembered as the founder of the eugenics movement. In June of 1873 he wrote a controversial letter to the Times entitled ‘Africa for the Chinese’, in which he argued that the Chinese, as a hard-working race capable of high civilization, should be encouraged to emigrate to Africa and displace the supposedly inferior aboriginal blacks. Shortly before his death at the age of 89, he completed his utopian eugenic novel ’Kantsaywhere’. It was rejected by his publisher, and most of the novel was subsequently burnt by his niece - although some fragments survive.

In summary, all of those diagrams are impressive data representations but lack interaction techniques and only show small datasets due to the missing support of computers and their computational power.
In this age of the personal computer, where complex pictorial representations of data can be produced at the press of a button or the click of a mouse, we tend to take statistical graphics very much for granted, and it is difficult to imagine how revolutionary the first simple charts were.

1.4.1 Exercises

1. Use Google Image Search to find different types of diagrams! Try to classify and categorize these diagrams by looking for different criteria either by the graphical primitives they use or by the data they visually encode!

2. In which diagrams do you detect commonalities to the statistical graphics invented by Beck, Minard, Snow, Nightingale, Playfair, and Galton?

1.5 Visualization Today

Information Visualization is a relatively young subdiscipline of computer science. Some years ago it seemed an appropriate means to analyze datasets visually. But in these days our stored datasets have already become that large that novel visualization techniques and interaction principles have to be designed with the goal to handle all the given data efficiently and effectively.
The diagrams created before the invention of the computer are sometimes denoted as infographics or statistical graphics because they are typically used to tell a story about data or to show pure statistical data. They inform a viewer about facts, normally datasets of smaller size displayed without allowing interaction. Nowadays, we speak of ordinary graphics, those that can be manipulated by interaction of the human user with the computer. Ever larger datasets are visually represented in an automatical and fast manner. But also today’s visualizations tell stories - stories about data.

Nowadays there is an increasing tendency to reproduce things visually, and this also applies to data. This data is not always invented as part of a larger concept. It is just data! But this data can tell a story as soon as it is visualized. Often more than words in a report can say. It almost becomes an emergent story, a story that comes into existence because the data is made visual. But is this then also just an infographic? Shouldn’t an infographic tell or illustrate a preconceived story, instead of just coming into existence? In this aspect the profession of data visualization borders on that of an artist. Visualization as it is understood today is also an infographic but it is also much more, see Figure 17 for an infographic.

![Fig. 17 An Infographic that shows the 'Life on Earth' as a node-link tree diagram. The story-telling behavior makes Infographics different from pure visualization of statistical data that are just straightforward encodings of statistical data.](image)

We, after the year 2000, live in a data-driven era. The amounts of generated and stored data is increasing by tremendous rates every day. The technical progress in hardware technology allows us to store all the data but the question arises why we store all the data when we are not able to analyze it. This means the data is worthless when it is sleeping unused in large text files and databases.

One way to make use of the wealth of data is to make it visible and allow to derive information from it. In this work we distinguish between data and information.

**Definition 1.5.1 (Data):** Data are facts, statistics used for reference and analysis
or numbers, characters, symbols, images etc., which can be processed by a computer. Data must be interpreted, by a human or machine, to derive meaning. Data is a representation of information.

**Definition 1.5.2 (Information):** Information is knowledge derived from study, experience (by the senses), or instruction. It is communication of intelligence. Information is any kind of knowledge that is exchangeable amongst people, about things, facts, concepts, etc., in some context. Information is interpreted data.

The main principle of information visualization is to

'Allow information to be derived from data.'

Visualization is needed to understand, explore, analyze data faster, better, and more reliably. Data comes in various forms which demands for many visualization techniques all designed for visually encoding one specific data form supporting the human viewer and analyst at solving specific tasks.

A combination of many techniques from different fields led to a novel area denoted as Visual Analytics. Not only visualization is used, also the human user with his perceptual abilities is important for an exploration process. Algorithmic concepts for both the data preprocessing and data handling as well as interaction techniques are intertwined in the very complex data analysis process.

Actually, a human is equipped with five senses that could all be used to obtain insights in a given dataset but human vision is the most effective one. The five senses are given in the following:

- **Sight (Ophthalmoception)**
- **Hearing (Audiocception)**
- **Taste (Gustaoception)**
- **Smell (Olfacoception or Olfacception)**
- **Touch (Tactioception)**

These senses are the five that are traditionally recognized. Senses are physiological capacities of organisms that provide data for perception. The senses and their operation, classification, and theory are overlapping topics studied by a variety of fields, most notably neuroscience, cognitive psychology (or cognitive science), and philosophy of perception. The nervous system has a specific sensory system or organ, dedicated to each sense.

Apart from these there are also some other senses, i.e. for balance and acceleration, temperature, kinesthetic sense, pain, time, and other internal senses.

Sight or ophthalmoception is actually the highest bandwidth sense meaning 100 megabytes of information per second can be processed which is the reason why we make data visible to our eyes with the goal to read, explore, and understand it very
fast. The human eye (see Figure 19) is an organ which reacts to light for several purposes. As a conscious sense organ, the mammalian eye allows vision. Rod and cone cells in the retina allow conscious light perception and vision including color differentiation and the perception of depth. The human eye can distinguish about 10 million colors [10].

Apart from being the highest bandwidth sense, vision is very fast and runs in parallel. It benefits from pattern recognition, parallel processing, extension of memory and cognitive capacities and allows pre-attentive processing, see the example in Figures 18 (a) and (b). All these aspects can be exploited to make it useful for Information Visualization.

Fig. 18 Q and C letter experiment: (a) A set of Q and C letters all colored in black is displayed. (b) The task of finding the C letters when they are given an extra visual feature (red color) gets easier - we say this task is pre-attentive.

Figures 18 (a) and (b) demonstrate one experiment illustrating pre-attentive processing! Letters with (red colored 'C' letters and black colored 'Q' letters) and with-
out color coding are represented. Three ‘C’ letters in a pool of ‘Q’ letter distractors are shown. The task for the viewer is to tell whether ‘C’ letters are present in the ‘Q’ letters or not. Pre-attentive processing means that a viewer can tell at a glance if the target object is present or not. This means at most 200-250 milliseconds are required to find this information. An eye fixation takes at least 200 milliseconds to initiate. This means the viewer has "only one look to the display". Consequently, no focused attention is needed to solve this task, hence the term pre-attentive processing.

As mentioned before, human vision benefits from the processing of 100 Mega-bytes per second and has the highest bandwidth of all senses (see the human eye in Figure 19), the ears only allow up to 100 bits per second. Even less allow the senses for smell, taste and the tactile sense.

Even if you got very enthusiastic about visualization there are also some scenarios where visualization is not the mean of choice. Generally, we can say:

- **Visualization is required**, when the goal is to augment human capabilities in situations where the problem is not sufficiently well defined for a computer to handle algorithmically.
- **Visualization is not required**, if totally automatic solution can completely replace human judgement.

Fig. 19  The human eye consists of several components. Only when those are interacting visual perception is possible.
Figure 20 When is visualization required? (a) A data scenario where visualization is of great help for us because what we see as a pattern or trend in this diagram cannot be computed by an algorithm at least not that easy. (b) Finding minimum or maximum values can be done by a bar chart but an algorithm can do better.

Figure 20 (a) shows a data scenario where visualization is of great help for us because what we see as a pattern or trend in this diagram cannot be computed by an algorithm at least not that easy. In Figure 20 (b) a dataset is displayed in form of a bar chart. If the task is to find minimum and maximum values such a visual representation is not required because a very simple algorithm can take the list of values as input parameters and decide in linear time which value is the minimal and which one the maximal one.

If we decide to use a visualization technique to graphically show our data we have several benefits, i.e. visualization is useful for:

- Generating new hypotheses when exploring a completely unfamiliar dataset
- Confirming existing hypotheses in a partially understood dataset
- Presenting information about a known dataset to another audience

When creating visualization techniques the visualization designer must be aware of a list of resource limitations:

- Technological and algorimtical limitations
  - Computational capacities: Is there an efficient algorithm?
  - Display capacities: How many objects can be rendered?

- Human limitations
  - Perceptual capacities: How many colors can be distinguished?
  - Cognitive capacities: How much can be remembered?
1.5.1 Exercises

1. Find three examples of datasets and tasks where visualization is really required and where not!

2. If we have to deal with a huge dataset and we would like to represent as much of the data as possible to the viewer what can we do and which problems will we face when the displayed data gets larger and larger?

2 Perception and Attention

Perception is one of the oldest and most fundamental disciplines within Psychology, dating back to at least the time of the ancient Greeks. The goal of perception research is to understand how stimuli from the world interact with our sensory systems, forming visual, auditory, tactile, olfactory, and gustatory representations of the world. Research in perception and psychophysics is directed at discovering the lawful relations between environmental events and subjective experience. This area spans a wide range of problems extending from the structure and function of the sense organs, through the processing of sensory information, to the nature of subjective experience and the methods by which an accurate description of these experiences is obtained. As such, an understanding of perception is critical for all areas within Psychology. The modern study of perception is highly integrative, combining cognitive, behavioural, computational, developmental, and neuroscientific approaches.

2.1 Visual Perception

Perception is very important for Information Visualization as well. How we perceive visually encoded datasets plays a crucial role in which insights can be derived from them and at what speed. Understanding the data that is represented can hence be improved by appropriately applying visualizations techniques that are designed by following laws given by research in perception theory.

**Definition 2.1.1 (Perception):** Perception (from Latin perceptio, percipio) is the process of attaining awareness or understanding of the environment by organizing and interpreting sensory information. This involves signals in the nervous system which result from physical stimulation of the sense organs. For example, vision involves light striking the retinas of the eyes, smell is mediated by odor molecules and hearing involves pressure waves.

**Definition 2.1.2 (Visual Perception):** Visual perception is the ability to interpret the surrounding environment by processing information that is contained in visible light. The resulting perception is also known as eyesight, sight, or vision (adjectival
form: visual, optical, or ocular). The various physiological components involved in vision are referred to collectively as the visual system, and are the focus of much research in psychology, cognitive science, neuroscience, and molecular biology.

As Goldstein [7] puts it: 'Perception is our window to the world that enables us to experience what is out there in our environment. Thus, perception is the first step in the process that eventually results in all of our cognitions. Paying attention, forming and recalling memories, using language, and reasoning and solving problems all depend–right at the beginning–on perception. Without perception, these processes would be absent or greatly degraded. Therefore it is accurate to say that perception is the gateway to cognition.'

The fundamental goal of visualization is to allow information to be derived from data by the production of images that support visual analysis, exploration, and discovery of novel insights. Human visual perception is a very deciding factor during the visualization design, i.e. when mapping a dataset to graphical primitives and their relations among each other but also when integrating interactive features. “How we see” the details in an image may impact a viewer’s efficiency and effectiveness. Consequently, an understanding of perception and attention can significantly improve both the quality and the quantity of information being displayed.

2.1.1 Exercises

1. Which visual features might be problematic from a perceptual perspective when designing a visualization technique?
2. What do you think is better from a perceptual point of view: An animated three-dimensional diagram or a static and two-dimensional one for depicting the same data?

2.2 Preattentive Processing

The question that might be interesting to ask in Information Visualization is how the human visual system analyses images? One important result to this question is the discovery of a limited set of visual properties that are detected very rapidly by low-level and fast-acting visual processes. Initially this effect was called preattentive because we do not need focused attention to solve those tasks involving graphical primitives with several visual properties. But later it was found out that attention plays a crucial role even at this early stage of vision. Although the term “preattentive” seems to be not quite correct it is still used today to express visual properties that “pop out” from the display. It is present in literature and replacing it by a different term is impossible, hence we must keep on using it.
**Definition 2.2.1 (Preattentive processing):** Preattentive processing of visual information is performed automatically on the entire visual field detecting basic features of objects in the display. Such basic features include colors, closure, line ends, contrast, tilt, curvature and size. These simple features are extracted from the visual display in the preattentive system and are later joined in the focused attention system into coherent objects. Preattentive processing is done quickly, effortlessly and in parallel without any attention being focused on the display [21].

There are some other definitions from several researchers:

- Typically, tasks that can be performed on large multi-element displays in less than 200 to 250 milliseconds (msec) are considered preattentive [9].
- Visualization is so effective and useful because it utilizes one of the channels to our brain that have the highest bandwidths: our eyes. But even this channel can be used more or less efficiently. One special property of our visual system is preattentive processing [13].
- One very interesting result of vision research over the past 20 years has been the discovery of a limited set of visual properties that are processed preattentively (i.e. without the need for focused attention). Typically, tasks that can be performed on large multi-element displays in 200 milliseconds or less are considered preattentive. This is because eye movements take at least 200 milliseconds to initiate. Any perception that is possible within this time frame involves only the information available in a single glimpse. Random placement of the elements in the displays ensures that attention cannot be prefocused on any particular location. Observers report that these tasks can be completed with very little effort [8].

![Fig. 21](image)

**Fig. 21** Preattentive visual feature: (a) Red target circle present in a sea of blue circles (distractors). (b) Red target circle not present in a sea of blue circles.

Figures 21 (a) and (b) show a scenario where the visual feature ‘color’ is used as a distinguishing feature. A red circle in a sea of blue circles is detected preattentively
The viewer can tell at a glance whether the red circle is present (Figure 21 (a)) or not (Figure 21 (b)). The target object in this scenario is identified through difference in hue, i.e. a red target in a sea of blue distractors.

Such a visual property that pops out from a display can be very useful for designing effective information visualization techniques. For example, if the task is to find anomalies or outliers as fast as possible these might be given a specific visual feature which is preattentively detected.

Not every preattentively detected visual feature works equally well. There are some features which are detected faster than others and also more accurately. For example, Figures 22 (a) and (b) illustrate a scenario of a red colored circular target object in a sea of red colored square distractor objects. Although it is detected preattentively the scenario with the red circle among all the blue circles works better. This means the specific hue differences (in this case red to blue) are stronger than the specific shape/curvature differences (in this case circular to square).

Fig. 22 Preattentive visual feature: (a) Red target circle not present in a sea of red squares (distractors). (b) Red target circle present in a sea of red squares.

Generally spoken, the pop-out effect is stronger in the scenario where the target object is identified by a difference in hue than in the scenario where it is identified in a difference in shape/curvature.

The question arises if there are scenarios, i.e. visual features which are not detected preattentively. The answer to that question is yes, there are such scenarios: If a red circle target object is to be checked for presence or non-presence in a group of red squares and blue circles (see Figures 23 (a) and (b)) we can find out by ourselves that it takes much longer to solve this task than the two tasks illustrated before (Figures 21 (a) and (b) and Figures 22 (a) and (b)).

The reason for this phenomenon is what is called a conjunction search. The target red circle contains two features at the same time, i.e. it is red and circular. This is actually not the problem but each of both features is in each of the distractor objects, i.e. we have to deal here with a group of red squares and blue circles.
Definition 2.2.2 (Conjunction Search): Conjunction search (inefficient search) occurs when the target and the distractors share similarities in more than one single visual property such as size, color, orientation and shape.

In a conjunction search our visual system has no unique visual property to search for the target location. A search for red elements sees red squares and a search for circular elements sees blue circles. Many studies showed that most conjunction targets cannot be detected preattentively, a time-consuming serial search must be performed to confirm presence or absence, instead.

From an information visualization perspective such a conjunction search can have bad consequences on the effectiveness of the designed visualization technique. Exploiting low-level visual processes in a visualization can be very useful to guide attention which can be drawn to areas of potential interest in a display. Consequently, such a data-feature mapping must take advantage of visual system strengths, i.e. it should be well-designed to the viewer’s analysis and tasks at hand and no visual interference effects should occur that consequently hide information or make them hard to locate by conjunction search.

Not only single elements can be detected preattentively but also boundaries might be detected when there is a common visual property which can be used to distinguish one group of elements from the others, see Figures 24 (a) and (b).

Apart from target and boundary detections, also region tracking and counting/estimation are investigated as preattentive visual tasks when conducting experiments in the field of psychology. Figures 25 (a) - (p) show examples of visual features from an endless list of features which are detected preattentively.

There exist five very prominent theories for preattentive processing: Feature integration theory, textons theory, similarity theory, guided search theory, and boolean maps theory.
Fig. 24 Boundary detection: (a) Red and blue elements can be clearly separated by a horizontal line right after the fourth row and this boundary is detected preattentively. (b) Red circles and blue squares cannot be separated from red squares and blue circles by a vertical line right after the fifth column in a preattentive manner.

In particular, in feature integration theory, Anne Treisman worked as a researcher in this field of preattentive processing. More specifically, she worked in the disciplines visual attention, object perception, and memory. She studied two major problems:

- The determination of which visual properties are detected preattentively and
- The formulation of a hypothesis about how the visual system performs preattentive processing

She conducted two types of experiments using target and boundary detection for preattentive feature classification. The preattentive performance task was measured by either response time or accuracy.

For the study design measuring the response times the viewers were asked to answer the task (target detection) as fast as possible by having a high level of accuracy. The number of distractor objects was increased for the scenes.

If the response time is relatively constant and below a given threshold this task is considered preattentive. Otherwise the viewers must apply search strategies to confirm or reject the presence or absence of a target. An increased number of distractors would consequently increase the time taken to answer the task.

For the study design measuring the accuracy the viewers were represented a scene for a small, fixed exposure duration and then it was removed. The number of distractor objects was varied for each stimulus. If the viewer answers the task correctly the feature used to define the target is called preattentive. The exposure duration threshold was given by 200 to 250 msec, because viewers can only have ‘one look’ at the stimulus.

By these experiments Treisman collected a list of visual features that are detected preattentively (see for example Figures 25 (a) - (p)). It may be noted that
Fig. 25 Examples of preattentively detected visual features: (a) Line orientation. (b) Length/width. (c) Closure. (d) Size. (e) Curvature. (f) Density/Contrast. (g) Number. (h) Color/Hue. (i) Luminance. (j) Intersections. (k) Terminators. (l) 3D Depth. (m) Flicker. (n) Direction of Motion. (o) Velocity of Motion. (p) Lighting Direction.

some features have an asymmetric behavior. For example, a sloped line between many vertical lines is detected preattentively whereas a vertical line between many sloped lines is not detected preattentively. There is an effect of types of background distractors.

Her model of low-level human vision is made up of a set of feature maps and a master map of locations, see Figure 26. Each feature map registers activity for a specific visual feature. There is a manageable number of feature maps, i.e. for example one for each of the opponent colors, or separate maps for orientation, shape, and texture, and so on. When the visual system first ‘sees’ an image all features are encoded in parallel in the corresponding feature maps.

If the target has a unique visual feature the corresponding feature map is simply accessed. A conjunction target cannot be detected by accessing an individual feature
map. The target location needs a serial search through the master map of locations and focused attention requires a relatively large amount of time and effort.

2.2.1 Exercises

1. Which visual features work better and which ones worse for preattentive processing? Have a look at Figures 25 (a) - (p) and try to find an order among the visual features!
2. How can you make use of preattentive processing for designing better and more efficient information visualizations?

2.3 Visual Memory

Preattentive processing asks, what visual elements pop out from the display and put our focus of attention to a special region on screen. But there is also another important question which is, what is remembered about a visual element when we look at a different region on screen. This is very important in order to design a good visualization technique. The viewer must remember the location of display areas and the graphical primitives they contain. On the one hand he must compare visual patterns shown in a specific area on screen with other visual patterns in other regions on screen. In many cases this process is conducted several times, i.e. the eyes are looking to and thro until the comparisons give some insights.

Such comparisons are not that easy as one might think. We are not constructing a high-resolution and detailed description of the world around us. Instead, researchers
in psychophysics showed that we have a very limited short term memory and that the viewer’s current state of mind plays a deciding role in detecting visual phenomena or not. This means we are not able to remember many regions from a visualization with the goal to draw conclusions but we instead get the information when it is needed. This fact makes the visual exploration of a complex visualization technique very challenging.

There are five theories describing what is going on when the human viewer is using his visual memory: Postattentive amnesia, memory-guided search, change blindness, inattentional blindness, and attentional blink.

![Fig. 27](image)

Fig. 27 Postattentive amnesia studied by Jeremy Wolfe: (a) Target is told before showing the scene. (b) Scene is first shown than the target.

In particular, for postattentive amnesia Jeremy Wolfe [23] conducted a study which shows interesting results. There are two scenarios tested during the study. In the first scenario a viewer is told which target is of interest before showing him a scene containing several graphical elements of relatively simple shapes, see Figures 27 (a) and (b). In the second study scenario the scene is first shown to the viewer and then the target of interest is shown as textual information in the center. The question that Wolfe asked was which of the two experiments performs better?

There was an interesting result in this study. The assumption before having conducted the study was that seeing the scene first then the description helps for detecting the target and consequently, performs better. Wolfe’s study unhides a totally different result, i.e. this assumption is not true! No additional information is ‘saved’ in the visual system after focus of attention is put to new visual elements which again shows that the human viewer cannot remember several graphical elements in a visualization in order to compare them with others.
Another theory is explained by change blindness. This is defined as ‘the difficulty in detecting changes in scenes.’ The signification of attention (or lack thereof) is very crucial in determining a change in a picture, scene, or environment. A study by Ronald Rensink [18] showed that pictures must be alternated from one to the other several times until participants were able to detect the difference. When a cue was added indicating where particular changes are in the picture, participants performed faster. Search images as are known from magazines are very common also for laymen, i.e. the single task in such search images is to locate a given number of differences between two simultaneously side-by-side shown images, see Figures 28 (a) - (b). The effect of change blindness also depends on the complexity and the degree of abstractness in the displayed images, see for example Figures 29 (a) and (b).

![Fig. 28](image_url) Change blindness is a known problem when comparing images: (a) Original image. (b) Image with several changes (differences to the original image).

Change blindness is not just limited to pictures, this phenomenon can also occur in movies. A scene that should be the same differs from one shot to the next. This phenomenon is known as the continuity error and those are searched for in a movie by special viewers which is a difficult task even if the movie is very well known. The movie has to be watched many times to uncover the differences and those may even not be found out if a viewer is not instructed to search for them. Research in psychophysics indicates that a short interruption in a scene may make a viewer blind to significant differences in the scene during the interruption.

Many viewers have difficulties to detect the differences. Even if they are told to inspect the image carefully those differences are not found. Once they find them they agree that it was trivial to find them. Change blindness is not caused by a limited visual acuity but by inappropriate attentional guidance.

In the experiments by Levin and Simons [14] participants had to watch a short movie. Then the central character in the movie was switched in a so called cut
scene. The study participants were not instructed to search for something. After the movie, they were asked about something special. The results show that nearly 66 percent of the participants did not notice that the actor was changed. 70 percent of the participants did not see the change but described the central character by details from the initial one.

Fig. 29 Also the change blindness effect can be stronger when the shown images are more complex and more abstract: (a) Original image. (b) Image with several changes (differences to the original image).

Fig. 30 The workmen with door experiment shows the effect of inattentional blindness.

Inattentional blindness is related to change blindness. Viewers can totally fail to perceive visual elements or activities which in this case is caused by an absence of attention to the unseen object. This means a clear evidence of the importance of attention for perceiving. Also for this phenomenon important experiments have been conducted. The invisible gorilla test [19, 3] shows that people totally fail to see a black colored gorilla when they have to count the ball contacts of a basketball team dressed in white (the opposite team is dressed in black as the gorilla). Another experiment is called workmen with door and shows a person which is asked for the way in a city. The other person has a map in his hands. Then two workmen carrying a door separate both actors from the beginning. In this moment the original actor
is exchanged by someone else. In many cases, the person asked for the way totally fails to notice the change, see Figure 30.

Inattentional blindness hence expresses that we focus our attention on something which lets us totally fail to perceive other phenomena as illustrated in the invisible gorilla test as well as in the workmen with door test.

2.3.1 Exercises

1. Design an inattentional blindness test by yourself! Conduct the study and find out some interesting results.
2. Find information visualization where postattentive amnesia, change blindness, or inattentional blindness play a crucial role for the effectiveness of the visualizations!

2.4 Gestalt Theory

How we perceive visualizations is very important for information visualization. As discussed before, designing a visualization technique effectively by letting interesting elements pop out from the display or making graphical primitives or complete scenes memorizable from one gaze to the next or even over longer durations can be understood by principle from preattentive processing or research on the visual memory. Another very important principle when designing visualizations is what researchers called 'Gestalt theory'.

Gestalt psychology or gestaltism (German: Gestalt - 'essence or shape of an entity's complete form') is a theory of mind and brain of the Berlin School. The operational principle of Gestalt psychology is that the brain is holistic, parallel, and analog, with self-organizing tendencies. The Gestalt effect is the form-generating capability of our senses, particularly with respect to the visual recognition of figures and whole forms instead of just a collection of simple lines and curves. The phrase 'The whole is greater than the sum of the parts' is often used when explaining Gestalt theory.

There are five key principles of Gestalt theory that are: Emergence, reification, multistability, invariance, and grouping.

2.4.1 Emergence

The key principle of emergence is defined as the process of complex pattern formation from simpler rules. It is demonstrated by the perception of the black and white picture of a Dalmatian dog sniffing the ground in the shade of overhanging trees, see Figures 31 (a) and (b). The dog is not recognized by first identifying its parts
(feet, ears, nose, tail, etc.), and then inferring the dog from those component parts. Instead, the dog is perceived as a whole, all at once.

![Fig. 31 A Dalmatian dog is sniffing the ground in the shade of overhanging trees: (a) Difficult to detect the Dalmatian dog. (b) Showing the outline helps to detect the dog.](image)

Another picture where the principle of emergence is used to find a complex pattern is given in Figure 32. Here, you should look for an animal (a cow, i.e. only the head of a cow is visible). We leave this task open for the reader.

![Fig. 32 If you look carefully you might recognize a cow.](image)

2.4.2 Reification

The principle of reification is the constructive or generative aspect of perception, by which the experienced percept contains more explicit spatial information than the sensory stimulus on which it is based. For example in Figure 33 (a) a triangle is perceived, although no triangle has actually been drawn. In Figures 33 (b) and (d) the eye will recognize disparate shapes as 'belonging' to a single shape, in Figure 33 (c) a complete three-dimensional shape is seen, where in actuality no such thing is
drawn. Reification is explained by progress in the study of illusory contours, which are treated by the visual system as ‘real’ contours.

\[\text{Fig. 33} \quad \text{The Gestalt principle of reification can lead to the perception of objects that are not actually drawn: (a) A triangle is perceived, although no triangle has actually been drawn. (b) and (d) The eye will recognize disparate shapes as ‘belonging’ to a single shape. (c) A complete three-dimensional shape is seen, where in actuality no such thing is drawn.}\]

\[\text{2.4.3 Multistability}\]

Multistability (or multistable perception) is the tendency of ambiguous perceptual experiences to pop back and forth unstably between two or more alternative interpretations. Examples are the Necker cube (Figure 34 (a)), Rubin’s Vase illusion (Figure 34 (b)), the three-legged blivet (Figure 34 (c)), and artist M. C. Escher’s artwork and the appearance of flashing marquee lights moving first one direction and then suddenly the other. Gestalt theory does not explain how images appear multistable, only that they do.

\[\text{Fig. 34} \quad \text{The Gestalt principle of multistability leads to ambiguous perceptual experiences: (a) The Necker cube. (b) Rubin’s vase illusion. (c) The three-legged blivet.}\]
2.4.4 Invariance

The principle of invariance is the property of perception whereby simple geometrical objects are recognized independent of rotation, translation, and scale. Also other variations such as elastic deformations, different lighting, and different component features are recognized, see Figures 35 (a) - (d).

Fig. 35 The Gestalt principle of invariance leads to geometrical objects to be recognized independent of rotation, translation, and scale.

The principle of invariance is explicitly apparent in captchas. A CAPTCHA (an acronym for ‘Completely Automated Public Turing test to tell Computers and Humans Apart’) is a type of challenge-response test used in computing to determine whether or not the user is human. The term was coined in 2000 by Luis von Ahn, Manuel Blum, Nicholas J. Hopper of Carnegie Mellon University and John Langford of IBM. The most common type of CAPTCHA was first invented by Mark D. Lillibridge, Martin Abadi, Krishna Bharat and Andrei Z. Broder. This form of CAPTCHA requires that the user type the letters of a distorted image, sometimes with the addition of an obscured sequence of letters or digits that appears on the screen. Because the test is administered by a computer, in contrast to the standard Turing test that is administered by a human, a CAPTCHA is sometimes described as a reverse Turing test. This term is ambiguous because it could also mean a Turing test in which the participants are both attempting to prove they are the computer. Figure 36 shows an example for several captchas.

Fig. 36 The Gestalt principle of invariance is explicitly used in CAPTCHAS.
2.4.5 Grouping

The key principle of grouping can be subdivided into six further subprinciples or laws: Law of proximity, law of similarity, law of closure, law of good continuation, law of common fate, and law of good form.

Law of Proximity

Perception tends to group stimuli that are close together as part of the same object and stimuli that are far apart as two separate objects. This allows for grouping together elements into larger sets, and reduces the need to process a larger number of smaller stimuli. People tend to see clusters of dots on a page instead of a large number of individual dots. Our brain groups together the elements instead of processing a large number of smaller stimuli which allows us to understand and conceptualize information more quickly, see Figures 37 (a) and (b).

![Fig. 37 The law of proximity: (a) A group of circles perceived as one group. (b) Circles perceived as three groups.](image)

Law of Similarity

Perception lends itself to seeing stimuli that physically resemble each other as part of the same object, and stimuli that are different as part of a different object. This allows for people to distinguish between adjacent and overlapping objects based on their visual texture and resemblance. Other stimuli that have different features are generally not perceived as part of the object. Our brain uses similarity to distinguish between objects who may lay adjacent to or overlap with each other based upon their visual texture. An example would be a field of flowers which differ only by color or a group of black and gray colored circles, see Figure 38.
Fig. 38 The law of similarity leads to perceiving circles of the same color as groups of circles.

Law of Closure

The law of closure is the mind’s tendency to see complete figures or forms even if a picture is incomplete, partially hidden by other objects, or if part of the information needed to make a complete picture in our minds is missing. For example, if part of a shape’s border is missing people still tend to see the shape as completely enclosed by the border and ignore the gaps, see Figures 39 (a) and (b). This reaction stems from our mind’s natural tendency to recognize patterns that are familiar to us and thus fill in any information that may be missing.

Closure is also thought to have evolved from ancestral survival instincts in that if one was to partially see a predator their mind would automatically complete the picture and know that it was a time to react to potential danger even if not all the necessary information was readily available.

Fig. 39 The law of closure: A circle (a) and a rectangle (b) are perceived although there are many gaps.

Law of Good Continuation

When there is an intersection between two or more objects, people tend to perceive each object as a single uninterrupted object. This allows differentiation of stimuli even when they come in visual overlap. We have a tendency to group and organize lines or curves that follow an established direction over those defined by sharp
and abrupt changes in direction. An example for this are the two keys overlaid by each other as represented in Figure 40.

![Fig. 40](image)
The law of good continuation leads to perceiving the two keys by following an established direction.

**Law of Common Fate**

Visual elements moving in the same direction at the same velocity are perceived as one large object. An example is a bird swarm distinguished from background as one single moving object (though each single bird may be seen as small object), see Figure 41. More than one swarm of birds may cross each other in our visual field but those are then perceived as different swarms.

Our visual system is very sensible to moving objects even when other details are obscured. The evolutionary origin helps us to survive (uncover camouflaged predator from its background). The law of common fate is also used in user-interface design, i.e. the movement of a physical mouse is synchronized with the movement of mouse cursor seen on the computer screen.

![Fig. 41](image)
The law of common fate leads to perceiving a bird swarm distinguished from background as one single moving object.
Law of Good Form

The principle of good form refers to the tendency to group together forms of similar shape, pattern, color, etc. Even in cases where two or more forms clearly overlap, the human brain interprets them in a way that allows people to differentiate different patterns and/or shapes. An example would be a pile of presents where a dozen packages of different size and shape are wrapped in just three or so patterns of wrapping paper.

Figures 42 (a) to (c) show three scenarios of crossing or non-crossing patterns. This depends on how we perform the ’good form’ in each of the figures. Figures 42 (b) and (c) are enhanced by color coding to illustrate the different separation into graphical objects.

2.4.6 Exercises

1. Look for scenarios in your daily life where you apply Gestalt principles!
2. How can we exploit the Gestalt law of common fate for data that is changing over time?

2.5 Optical Illusions

When designing information visualizations we have to be careful to not produce a visual depiction of data which treats similar datapoints very differently. If so, this can cause misinterpretations of data. One very common problem occurring when using graphical objects is denoted by optical illusion. For example, two objects physically having the same color may be perceived as having different colors. Moreover, two bars having exactly the same length may be perceived as having different ones. Such a behavior is unfortunate because it introduces some kind of lie factor.

Definition 2.5.1 (Optical Illusion): An optical illusion (also called a visual illu-
sion) is characterized by visually perceived images that differ from objective reality.

Figure 43 shows the optical illusion often denoted as rotating snakes illusion originally designed by Kitaoka and Ashida [12]. The Rotating Snakes illusion, produced as a piece of Op-Art by Akiyoshi Kitaoka in 2003, belongs to the class of 'Peripheral Drift' illusions. These illusions evoke the perception of apparent motion from stationary images viewed in the periphery of the visual field. The illusion should be viewed in the peripheral vision and can be sustained by eye movement, blinking or flashing the image. The use of color in the illusion has been reported by Kitaoka to enhance the effect of the illusion, but a greyscale version of the illusion still evokes a strong perception of rotation. In fact, the only study to formally evaluate the effect of color on the strength of the illusion reported no significant effect [5].

The fundamental building block of this illusion is a sequence of only 4 elements of varying luminance. This shows that only with a few graphical elements a visual feature can be achieved which is not intended. This can have an impact on the interpretation of a visualization, i.e. the moving behavior may be interpreted as dynamics in the data which is not occurring in the data itself. Such effects make optical illusions worth investigating in Information Visualization. Here, also a lie factor comes into play. Generally, an optical illusion means a mapping of data to a visual feature that may lead to misinterpretations of the data, e.g. the perception of motion in a visualization showing a static picture of static data as illustrated in Figure 43.

Also of interest is the 'Spinning Dancer' illusion by Nobuyuki in 2003. Here, motion is perceived but depending on the viewer and its perceptual abilities the movement is either clockwise or counterclockwise. This optical illusion is also known as the silhouette illusion which is a kinetic, bistable optical illusion resembling a pirouetting female dancer. The illusion, created in 2003 by web designer Nobuyuki
Kayahara, involves the apparent direction of motion of the figure. Some observers initially see the figure as spinning clockwise (viewed from above) and some counterclockwise (Figure 44).

The illusion derives from the lack of visual cues for depth. For instance, as the dancer’s arms move from viewer’s left to right, it is possible to view her arms passing between her body and the viewer (that is, in the foreground of the picture, in which case she would be circling counter-clockwise on her right foot). And it is also possible to view her arms as passing behind the dancer’s body (that is, in the background of the picture, in which case she is seen circling clockwise on her left foot).

When she is facing to the left or to the right, her profile is unambiguous. That is, her breasts and ponytail clearly define the direction she is facing. However, as she moves away from facing to the left (or from facing to the right), the dancer can be seen (by different viewers, not by a single individual) facing in either of two directions. At first, these two directions are fairly close to each other (both left, say, but one facing slightly forward, the other facing slightly backward) but they become further and further away from each other until we reach a position where her ponytail and breasts are in line with the viewer (so that neither her breasts nor her ponytail are seen so readily). In this position, she could either be facing away from the viewer or toward the viewer, so that the two positions two different viewers could see are 180 degrees apart. Which the viewer sees will depend on which direction of turn the viewer is visualizing. There are other optical illusions that depend on the same or a similar kind of visual ambiguity. One example is the Necker Cube.

The judgement of different lengths is also a very important task in information visualization techniques. The Müller-Lyer illusion illustrates how simple attachments to equally long and parallel lines can lead to possible misinterpretations.

The horizontal lines in Figure 45 have the same length. The attached fins can point inwards to form an ‘head’ or outwards to form an ‘tail’. The line
Fig. 45 The Müller-Lyer illusion illustrates how simple attachments to equally long and parallel lines can lead to possible misinterpretations.

segment forming the shaft of the arrow with two tails is perceived to be longer than that forming the shaft of the arrow with two heads. The perception of the Müller-Lyer illusion varies across cultures and age groups.

Fig. 46 In the Hering illusion two straight and parallel lines look as if they were bowed outwards.

A second optical illusion going in the same direction is the so called Hering illusion. Here, two parallel lines are perceived as being non-parallel, see Figure 46. It was discovered by the German physiologist Ewald Hering in 1861. Two straight and parallel lines look as if they were bowed outwards. The distortion is produced by the radiating pattern and was ascribed by Hering to an overestimation of the angle made at the points of intersection.

In this category of misinterpreted parallelism we can find many other optical illusion examples such as the bricks, the wavy, the bulge, or the Zöllner illusions, see Figures 47 (a) - (d).

Even if nothing is displayed our visual system might give us the impression as if there are graphical elements, see Figure 48. If we look closely at this matrix of black squares we see, while scanning over the matrix, something peculiar in the intersections of the white crosses formed by the black squares. If you see dark blobs, don’t
Fig. 47 (a) The bricks illusion. (b) The wavy illusion. (c) The bulge illusion. (d) The Zöllner illusion.

be surprised, that is what most people see. This figure is called the Hermann grid after L. Herman (1870). The dark blobs can be explained by reference to receptive fields and lateral inhibition.

Fig. 48 In this matrix of black squares we see something peculiar in the intersections of the white crosses formed by the black squares which is called the Hermann grid illusion.

Another very important visual feature used in information visualization is color which has also be used with care. Several optical illusion can occur when not being
careful. As we can see in the checker board shadow illusion in Figure 49 the colors of the squares labeled A and B look different although they are exactly the same.

![Fig. 49 The checker board shadow illusion: What is the color of A and B compared to eachother?](image1)

The checker shadow illusion is an optical illusion published by Edward H. Adelson, Professor of Vision Science at MIT in 1995. The image depicts a checkerboard with light and dark squares. The optical illusion is that the area of the image labeled A appears to be a darker color than the area of the image labeled B. However, they are actually exactly the same color. This can be proven using the following methods:

- Opening the illusion in an image editing program and using the eyedropper tool to verify that the colors are the same.
- Isolating the squares. Without the surrounding context, the effect of the illusion is dispelled. This can be done by using the selection tool in some image editing programs.
- Using a photometer

![Fig. 50 The Rubik’s Cube illusion: The square in the top center and the one in the center of the cube’s front side look totally different (brown vs. orange).](image2)

A similar color perception phenomenon occurs in the Rubik’s Cube illusion. The same color is perceived differently caused by different surrounding color. The square in the top center and the one in the center of the cube’s front side look totally
different (brown vs. orange), see Figure 50. Of interest to us in this illusion are only
the central pieces of each of the three visible sides. Two sides are lit and have a
brown tile in the middle. The side in shadow has a yellow tile in the middle. Or does
it? Use the color picker in any imaging software and you’ll find all three central tiles
are exactly the same color.

There are also several other color perception illusion as can be seen in Figures 51
(a) and (b). Figure 51 (a) shows a grey stripe on a gradient background. The stripe
appears to be shaded with a grey gradient also, however if you look closely you’ll
see that in reality the stripe is the same color all the way across. In Figure 51 (b) two
vertical grey stripes once integrated and once covered by black colored horizontal
parallel stripes can be seen. Although they look different in color also here it is
exactly the same.

![Figure 51](image)

Fig. 51 Color perception illusions: (a) A grey stripe on a gradient background. (b) Two vertical
grey stripes integrated and covered by black colored horizontal parallel stripes.

Also area sizes can underly optical illusions. The Ebbinghaus illusion (Figure 52)
indicates that the context may be a deciding factor when judging circle sizes. The
orange circles in the center seem to differ in size although they are exactly the same.

![Figure 52](image)

Fig. 52 The Ebbinghaus illusion: The circle sizes look different although they are exactly the same.

Also our experiences play a crucial role for what we see or perceive in a displayed
image. Figures 53 (a) to (c) are illustrations for such phenomena.
Fig. 53 Pattern perception by experience: (a) Young or old woman? (b) A face or not? (c) A skull or Santa Claus?

2.5.1 Exercises

1. Are there datasets for which a visualization technique must be more carefully designed than for other in order to avoid optical illusions?
2. Which tasks might be problematic to solve by a visualization technique when it contains some optical illusion?

References