Chapter 3
Perception

In the previous chapter, we saw how visual mapping is the most critical aspect in designing a visual representation. Views generated by these processes create strong visual representation of data because the elements we use to encode this data (lines, points, shapes, color, etc.) are processed by visual perception rapidly and efficiently. Mapping data attributes to proper graphical elements and properties is paramount to creating effective visual representation of data. The designer of such systems has to have a sound knowledge of how the different types of visual attributes are perceived by human vision. In a visual representation that aims to discover patterns in data, if the attributes are mapped in a certain way, the patterns are easily perceivable, while they become invisible when mapped in other ways. The "trick" is to visually represent data in such a way that the most important patterns are encoded with "popping-out" visual forms, clearly distinguishable from their surroundings. Due to the importance of mapping data effectively, this chapter contains the principles of visual perception with practical indications.

3.1 Memory

The term "memory" has slightly different meanings when used in different contexts. In computers, the memory is the part of hardware dedicated to storing data and can be accessed upon request. Data are encoded in binary values and are processed by the central processing unit (CPU) by means of programs; hence, in computers, there is a clear distinction among data, process, and programs. In organisms, the memory is a function of the brain, which is not only able to store information, but also to process and reason, and it constitutes the common ground for perception, categorization, interpretation, thinking, etc., all in the same organ (although certain activities are localized in specific areas of the brain). In fact, we receive light through the eye, which generates a visual stimulus. This stimulus is translated into neural signals by the retina and passed to the brain, where it is processed and perceived.

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Hence, it is in the brain that we perceive the images, make sense of them, and store our memories.

Cognitive psychology identifies several types of memories. With the aim of understanding how visual representation is perceived and stored in memory, it is worth mentioning the following types of memory, based on the duration of memory retention:

- **Sensory memory** is the ability of the brain to retain impressions of signals coming from sensor organs for a very short period of time, between 250 and 500 milliseconds or less. Visual sensory memory is more commonly referred to as *iconic memory*. This type of memory is able to store visual information from the eyes, independent of conscious control, and automatically. For this reason, the processing that takes place in iconic memory is called *preattentive processing*, as it is processed without the need for focused attention [57]. During preattentive processing, only a limited set of visual attributes is detected. Such basic features include colors, closure, line ends, contrast, tilt, curvature, and size [57].
- Some of the information in sensory memory is then transferred to **short-term memory**, where it remains from a few seconds to a minute (without rehearsal). If it is periodically rehearsed, it can remain for a few hours. This memory has limited storage capacity (some experiments showed that the store of short-term memory is between five and nine equally weighted items [44]), is conscious, and involves an attentive process of perception. The capacity of the short-term memory can be increased when information is organized in *chunks*, such as when we memorize phone numbers: By memorizing a number as several chunks of two or three numbers, it is easier to remember than when we try to memorize it as a simple sequence of digits. In visual representations, an example of a chunk of information is when, in a bar chart, we encode a categorical attribute with bars of different colors. A chunk of information (for instance, the information encoded with blue-colored bars) can be kept in the viewer's short-memory very efficiently. It is important, however, not to provide an excessive number of chunks that the viewer has to retain in memory.
- Information in short-term memory is easily forgotten after a brief period of time unless we rehearse it periodically or make meaningful associations. This type of memory can store information for many years, even for life, and is called **long-term memory**. Short-term memories became long-term by reinforcing the structure of neuronal synapses through a process called *long-term potentiation*.

The properties of sensory, short-term, and long-term memory have important implications in the design of a visual representation. In particular, preattentive visual processing, which takes place in the sensory memory, is fundamental for creating visual representations, as preattentive visual attributes are perceived by the reader almost instantaneously, without the intervention of consciousness. These attributes "pop out" from their surroundings [65]; therefore, most important data attributes, or items that have to be represented together as a group, should be encoded with preattentive attributes. These attributes will be described in detail later in this chapter.

In visual representations, mapping information is usually retained in the short-term memory. Since this type of memory has limited capacity and holds information for a few seconds, designers of visual representations shouldn't constrain users to remember more than nine chunks of information. For instance, if you design a chart that maps different data types with different shapes, there should not be more than nine data types (although less than five is ideal), and you should avoid splitting a representation into multiple windows (or request the user to scroll through the window), because if the image is no longer visible, the user has to retain a large quantity of data in short-term memory.

3.2 Preattentive Properties

Thanks to some studies in psychology, a number of visual properties that are preattentively processed have been identified [57]. According to Colin Ware [65], these can be grouped into four basic categories: *color*, *form*, *movement*, and *spatial position*. We will look at them in the following paragraphs.

3.2.1 Color

Colors can be expressed in different mathematical models. One of these is the *HSL* color system, which stands for *hue*, *saturation*, and *lightness*. Each color can be described by the composition of these three elements. In particular, the hue is the aspect of a color that we describe with names such "red," "green," etc. Saturation and lightness are related concepts that refer to the intensity of a specific color.

Hue and intensity are processed preattentively and work very well in the visual detection of elements that are distinguished from the surroundings, without the need for a sequential search, as in Fig. 3.1, where the letter C "pops out" from others because of the use of a preattentive attribute of hue (top) and intensity (bottom).

3.2.2 Form

Preattentive attributes of form are listed in Table 3.1, together with an example. Examples of preattentive attributes of form are also depicted in Fig. 3.2.

3.2.3 Spatial Position

The following are preattentive attributes of spatial position:

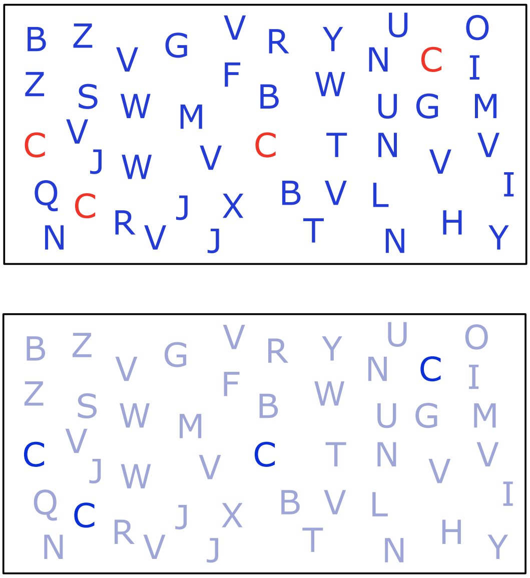

Fig. 3.1 Example showing how the hue and intensity of colors are processed preattentively, resulting in a quick distinction of elements.

- **2D position**, as we have seen in Fig. 2.4, is the most accurate attribute for encoding quantitative data in graphs.
- **Stereoscopic depth** is the result of the combination of the images received by both eyes. Thanks to the difference in the image location of an object seen by the left and right eyes (called *binocular disparity*), human eyes are able to preat-

Attribute	Example
Orientation	A line with a different orientation than the others
Length	The length of bars in a bar chart, as we have seen in Fig. 1.2
Width	The width of the line that we use to highlight parts of a figure
Size	The size of a shape, to rank a particular data attribute
Collinearity	Lines that follow the same direction
Curvature	Lines and object borders can be straight or curved
Spatial grouping	Groups of objects, such as a cluster
Added marks	Adding a mark in a set of objects to highlight one in particular
Shape	A square in a group of circles
Numerosity	Cardinality in groups of objects

Table 3.1 Preattentive attributes of form.

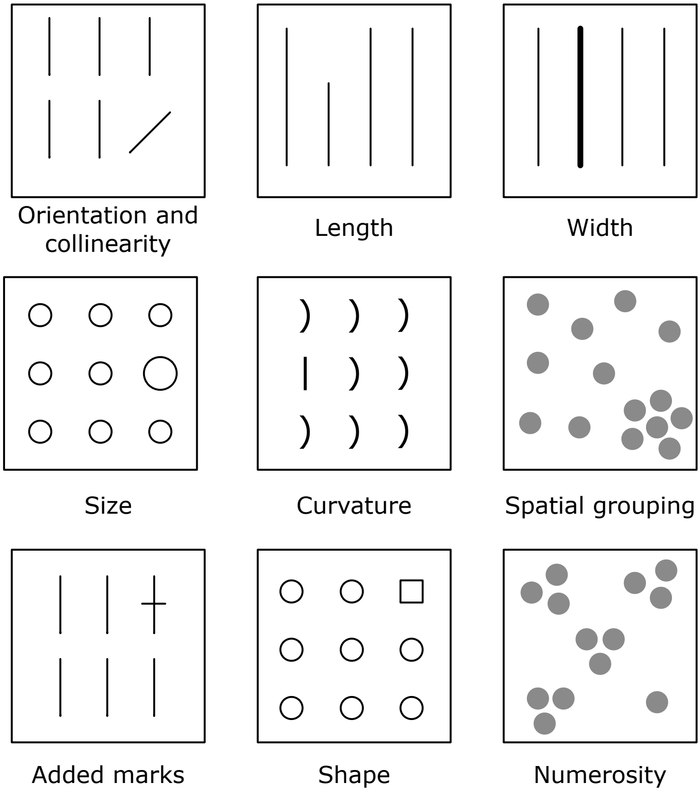

Fig. 3.2 Preattentive attributes of form.

tentively perceive depth. Stereoscopic vision can be reproduced by a computer using two different cameras.

- **Concavity/convexity** is produced in images through the effect of shading, such as the example given in Fig. 3.3.

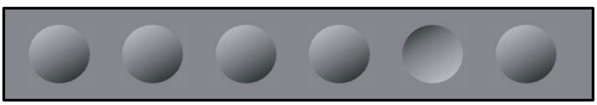

Fig. 3.3 Preattentive attributes of concavity/convexity.

3.2.4 Movement

Attributes of movement are **flicker** and **motion**. These are the most effective ways to get our attention. Often abused in websites (fickering advertisements are always annoying), they are used in dashboards as powerful attention-getters in situations that require immediate user intervention.

3.3 Mapping Data to Preattentive Attributes

The designer of a visual application has to carefully consider the attributes to be mapped into the visual presentation and decide which graphical property to use for each data attribute. This process is called visual mapping and has already been discussed in Section 2.1.2. In the light of what we have seen in this chapter, it is clear how visual preattentive attributes are very powerful, as they are immediately perceived without the need for conscious attention. Colin Ware describes these visual attributes as "the most important contribution that vision science can make to data visualization" [65]. However, this mapping cannot be done automatically, as the number of preattentive attributes that can be used in a single representation, and the number of visual distinctions of a single attribute, are limited. These limitations are due to our short-term memory feature that has to process the meaning of each encoding.

For instance, we can use distinct shapes or hues to represent census data in different years. This can work if the number of years is limited; if the number of years is very large, the encoding becomes inefficient, as readers are only able to distinguish a limited number of shapes or hues. Ware [65] suggests limiting to no more than eight different hues, four different orientations, four different sizes, and all the other visual preattentive attributes to less than 10 distinct values. Few [19] instead chooses a more prudent approach and suggests limiting the number of distinctions, for any attribute, to no more than four.

A similar limitation exists on the number of visual attributes that we adopt in a representation. Also, the combination of particular preattentive attributes cannot usually be detected preattentively. Let's look at the latter case with an example, illustrated in Fig. 3.4. The identification of gray squares is very slow, as the combination of gray-colored objects and square-shaped objects is not preattentive: We are forced to do a serial scan to locate the gray squares.

Now the point is: I have a dataset with a particular attribute to represent. Which preattentive attribute should I choose for it? We have already seen in Fig. 2.4 that Cleveland and McGill empirically verified that some attributes are more accurate than others for judging quantitative values. But we may also have categorical and ordinal types of attributes. Some scientists have addressed the issue of finding a mapping between data types and preattentive attributes. One of them, Mackinlay [39], even proposed a ranking of the accuracy of perceptual tasks that can be defined when encoding quantitative, ordinal, and categorical data with different graphical el-

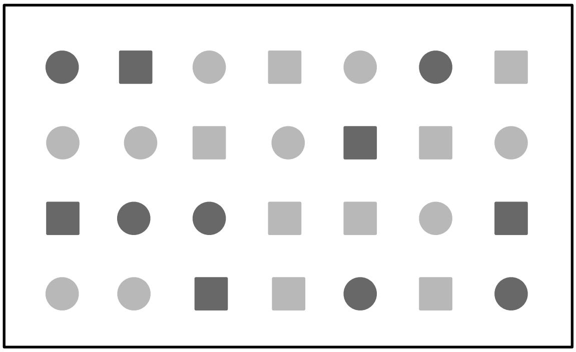

Fig. 3.4 Combinations of more preattentive attributes (in the image, lightness and shape) may prevent the preattentive identification of an object.

ements and properties. But recent studies have shown that things are more complex than they appear, and many factors influence the choice of encoding [55]. Therefore, a universal, generic, ranking of preattentive attributes does not exist. However, it does not mean that an indicative rule of thumb cannot be arranged. Some preattentive attributes work better with quantitative data types, while others are more effective with categorical or ordinal data types. Table 3.2 (inspired by a work by Stephen Few [19] and extended with the ordinal and categorical data types) can help in this.

3.4 Postattentive Processing

When we look at a bar chart, such as the one depicted in Fig. 2.7, we can immediately perceive the different lengths of the bars. As we have seen, this process is performed preattentively. Then we must turn our attention to the text on the horizontal axis to detect which country corresponds to the longest (or shortest) bar. Now we can leave the chart and look at something else (for instance, the single-axis scatterplot on the left). What happens when the attention is taken away from the bar chart, concentrates on something else, and then focuses on the chart once again? Does the viewer gain a richer understanding of the bar chart when the attention is applied to the chart the second time?

This aspect, called *postattentive processing*, was studied by Wolfe et al. [68]. They ran some experiments and found that attention has no cumulative effects on visual perception. In other words, if a viewer looks at one scene numerous times and then looks at something else, the new preattentive representation (or postattentive representation) of an object appears to be identical to its representation before the viewer focused his attention on it. The preattentive visual perception doesn't save any information about the scene. The viewer may know more about an ob-

Attribute	Quantitative	Ordinal	Categorical
Color			
Hue	×	×	√
Intensity	−	√	×
Form			
Orientation	−	−	×
Length	√	−	×
Width	−	−	×
Size	−	−	×
Collinearity	×	×	×
Curvature	−	−	×
Spatial grouping	×	×	×
Added marks	×	×	√
Shape	×	×	√
Numerosity	√	√	×
Spatial position			
2D position	√	√	−
Stereoscopic depth	×	×	×
Concavity/convexity	−	−	×
Movement			
Flicker	×	×	−
Motion	−	−	×

Table 3.2 Encoding quantitative, ordinal, and categorical data with different preattentive attributes. √ indicates that the attribute is suitable for the data type. − indicates a limited suitability. × indicates that the attribute does not work well with that data type.

served object after focusing on it again, but that knowledge does not alter the visual representation that the viewer has, in his mind, of that object.

This result has important implications on how visual representations are perceived. In particular, previewing a scene or paying prolonged attention to the objects does not make a visual search more efficient. Each object is recognized individually. Even if we study a display, we must apply the same preattentive effort to locating a particular object in a new, different scene. We cannot teach or improve viewers' preattentive capabilities.

3.5 Gestalt Principles

When we look at a image, such as the one depicted in Fig. 3.5, we can easily recognize that it represents a little house. But if we observe it in more detail, we can see how this image is a simple composition of a triangle and three rectangles that, arranged as in Fig. 3.5, lets us perceive an image portraying a little house rather than four simple geometric elements.

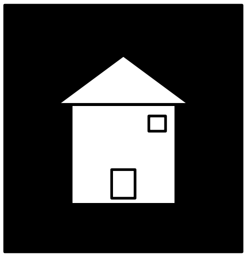

Fig. 3.5 A composition of simple geometric elements (triangle and rectangles) is perceived as a little house.

This phenomenon was studied by Gestalt theorists (in particular, Max Wertheimer [66], Wolfgang Köhler [35], and Kurt Koffka [34]) starting in 1920, who determined innate mental laws by which objects were perceived. Gestalt's basic principle is that the whole (the picture of the house) is not the simple sum of its parts (the triangle and rectangles) but has a greater meaning than its individual components. Gestalt principles aim to define the rules according to which human perception tends to organize visual elements into a "unified whole," also referred to as groups (from which the German term *gestalt* derives.) They are still valid today and can offer interesting insights into the design of visual representations. These principles are discussed next.

3.5.1 Figure and Ground

The figure and ground principle states that our perception tends to separate an object from its background, based on visual attributes, such as contrast, color, size, etc. A simple case is represented in Fig. 3.5. In this case, the image is perceived as being articulated into two components: the figure (the little house) and the ground (the black background).

3.5.2 Proximity

The proximity principle states that when elements are placed close together, they tend to be perceived as forming a group. See, for instance, Fig. 3.6. In the image to the left, squares are placed without proximity and so are perceived as 12 separate elements. In the central image, we see squares forming four groups. Even if the shapes or colors of the objects are different, they will appear as a group, as can be seen in the image on the right.

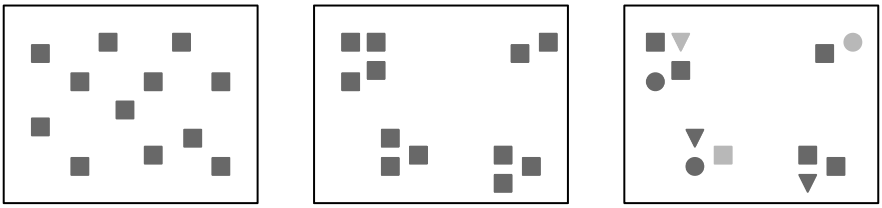

Fig. 3.6 Gestalt proximity example: Objects are perceived as separate elements (left) or as groups (center and right).

3.5.3 Similarity

The similarity principle states that objects with similar shape, size, color, orientation, and texture are perceived as belonging together, forming a group. In Fig. 3.7 on the left, objects of two distinct sizes seem to belong to the same group. Also, in the figure on the right, the filled and empty squares are associated naturally and we tend to see alternating rows of filled and empty squares.

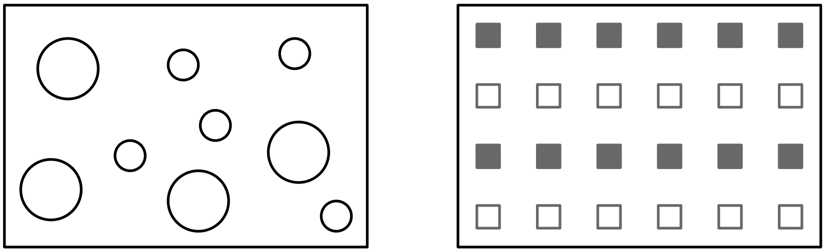

Fig. 3.7 Gestalt similarity example: Objects of the same size (on left) or different color (on right) are perceived as belonging to the same group.

3.5.4 Closure

The closure principle states that when an object is not complete, or the space is not completely enclosed, and enough elements are present, then the parts tend to be grouped together and we perceive the whole figure. See examples in Fig. 3.8.

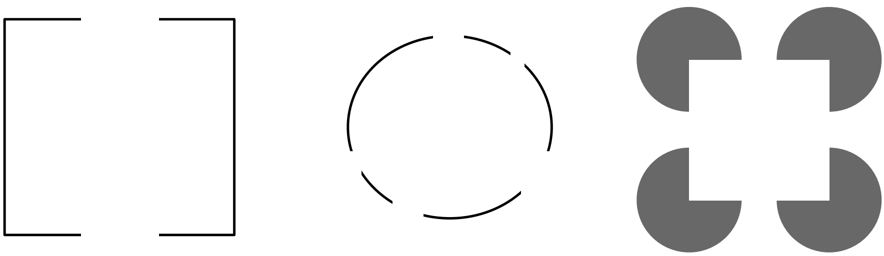

Fig. 3.8 Gestalt closure example: We tend to see complete figures even when part of the information is missing (left and center images) or when elements are aligned in such a way that the viewer perceives them as connected (right image).

3.5.5 Continuity

The continuity principle states that if an object appears to form a continuation of another object, beyond the ending points, we perceive the pieces as parts of a whole object. Some examples are depicted in Fig. 3.9. On the left, we see two triangles interrupted by a horizontal line; we don't see (although it could be another possible interpretation of the image) two small triangles laid on the line, and two trapezoids below. The same in the center and right images: We perceive an X sign (not four joint lines forming two symmetric corners), and the viewer's eye naturally follows the curved line, although it is interrupted and joined to another segment.

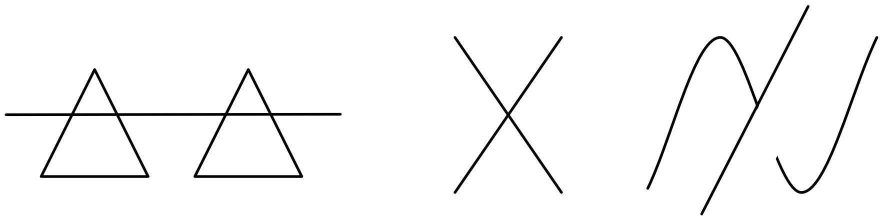

Fig. 3.9 Gestalt continuity example: Human mind naturally follow a line or a curve.

3.5.6 Other Principles

The Gestalt principles described above are the classics mentioned in literature, but there are several others, less common, that are not illustrated here. There is no definitive list of Gestalt principles, but we can mention the **common region principle** (objects enclosed by a boundary are perceived as a group), **connection principle** (objects that are connected are perceived as a group), and **symmetry principle** (symmetrical images are perceived as a group).

3.6 Conclusion

In this chapter, we have described the most important principles of visual perception. We have seen how short-term memory and preattentive processing play an extremely important role in the design of effective visual representations, where the most important information can "pop out" from the surroundings through the mapping of data with preattentive attributes. Also, the designer of visual representations can take advantage of the basic Gestalt principles, as they can offer interesting insights into the design of groups of elements.