Title
Visual Variables

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Word Count
4132

Abstract

The *visual variables* describe the graphic dimensions across which a map or other visualization can be varied to encode information. Twelve visual variables are introduced and discussed: (1) location, (2) size, (3) shape, (4) orientation, (5) color hue, (6) color value, (7) texture, (8) color saturation, (9) arrangement, (10) crispness, (11) resolution, and (12) transparency. The perceptual basis of the visual variables then is summarized, which informs use of the visual variables for univariate and bivariate mapping.

Main Text

Overview of the Visual Variables

The *visual variables* describe the graphic dimensions across which a map or other visualization can be varied to encode information. The visual variables originally were described by French cartographer and professor Jacques Bertin (CE 1918-2010) in the 1967 book *Semiologie Graphique.* The English translation *Semiology of Graphics* was released in 1983 and today is recognized as a seminal theoretical work in both Cartography and the broader field of Information Visualization. The visual variables were inspired by Bertin's reading of *semiotics*, or the study of sign systems. Semiotics seeks to understand how one object comes to stand for another object, and therefore helps cartographers think about the way in which a map symbol (the *sign vehicle* or *signifier*) representing a geographic phenomenon or process (the *referent* or *signified*) comes to mean something (the *interpretant*) to the map user. French semiotics was developed in linguistics as a method for deconstructing a language into its basic units in order to allow for description and comparison across different language sign systems. Following this approach, Bertin's visual variables describe the basic building blocks of a map or other visualization. By reducing the map into its constituent graphic elements, unclear or polysemic map symbols can be identified and redesigned, improving cartographic communication. Further, such deconstruction reveals the value judgments and power relationships implicit in the map design process, allowing for critical analysis of the social construction and cultural negotiation of meaning within the cartographic sign system.

Although the visual variables are an influential theoretical framework for cartographic design and research, the contents of visual variable taxonomies vary considerably by scholar (see Tyner, 2010, for a review). Figure 1 synthesizes several notable contributions within Cartography into a set of twelve of visual variables, adapted from MacEachren et al. (2012). While Figure 1 provides point symbol examples for each of the visual variables, the visual variables can be used to encode information about line and area features as well. Importantly, the following twelve visual dimensions only are considered visual ‘variables’ when functionally manipulated to encode information. Each of these visual dimensions also can be manipulated as design embellishments to improve the aesthetic quality of the map or visualization.

[place Figure 1 approximately here]

Bertin (1967|1983) originally identified seven visual variables that can be manipulated to encode information:

1. *Location* describes the position of the map symbol relative to a coordinate frame. Location is considered an ‘indispensible’ visual variable, and takes visual primacy over the others. In Cartography, location typically signifies the position of the map symbol relative to a projected spatial coordinate system, meaning that location primarily is used to represent the spatial component of information in cartographic design. However, location can be used to represent attribute information, such as the use of perspective height in prism maps. Further, isoline maps manipulate the visual variable location, interpolating attribute values to produce a spatial surface and then weaving isolines through locations of equal attribute values within this surface. In planimetric, two-dimensional representations, map symbols near the optical center tend to rise to *figure*, resulting in more immediate visual interpretation by the map user and thus landing them in a higher place of importance in the ‘visual hierarchy’. In contrast, map symbols near the periphery of the page tend to recede to *ground*, falling to the bottom of the visual hierarchy. In oblique or three-dimensional representations, map symbols that are perceived as nearer or taller tend to rise to figure.

2. *Size* describes the amount of space occupied by the map symbol. Size is the primary visual variable manipulated in proportional symbol maps and value-by-area cartograms. Size also is manipulated in flow maps that scale the thickness of the flow lines to an attribute value. Larger map symbols tend to rise to figure.

3 *Shape* describes the external form (i.e., the outline) of the sign vehicle. The visual variable shape is essential to the design of qualitative point symbols commonly used in reference mapping. The shape of these map symbols can vary from highly *abstract*, such as circles, squares, or triangles, to highly *iconic*, directly mimicking the referent represented by the map symbol. Map symbols that are more complex or less compact tend to rise to figure.

4. *Orientation* describes the direction or rotation of the map symbol from ‘normal’. The normal orientation typically is relative to the map’s neatline (either explicitly included or inferred by negative space), but in some cases can be relative to the projected spatial coordinate system (e.g., relative to the graticule) or another baseline. Multivariate glyph symbols typically make use of orientation to differentiate among the represented

attributes. Orientation also is manipulated in flow maps to represent the directionality of flow. Proximate groupings of map symbols that have the same orientation (either aligned or misaligned to normal) tend to rise to figure. Otherwise, map features that are misaligned to normal tend to rise to figure.

5. *Color hue* describes the dominant wavelength of the map symbol on the visible portion of the electromagnetic spectrum (e.g., blue, green, red), and is one of three visual variables associated with the perception of 'color'. Color theory occupies a substantial space in the cartographic canon (see Brewer, 2005, for a review) and is particularly relevant for choropleth mapping as well as other forms of reference and thematic maps that use colors to designate categories or classes. A *qualitative* or *spectral color scheme* manipulates color hue while controlling the other components of color; as explained below, such color schemes are appropriate for nominal choropleth maps only. Red map symbols tend to rise to figure while blue map symbols tend to recede to ground.

6. *Color value* describes the relative amount of energy emitted or reflected by the map symbol. Variation in color value results in the perception of shading, or areas of relative light (high emission or reflectance of energy) and dark (low emission or reflectance of energy). Accordingly, color value is sometimes referred to as 'lightness' in color theory. Manipulation of color value is important for choropleth maps depicting ordinal or numerical information. A *sequential color scheme* adjusts color value in one direction, sometimes crossing over two or three different color hues to improve discriminability. A *diverging color scheme* adjusts color value in two directions away from a critical midpoint, with each direction denoted by color value changes within a different color hue. A variation on a spectral scheme with the green hues removed also is effective as a diverging color scheme. The figure-ground relationship for color value is relative to amount of light and dark areas on the map. Map symbols that are dark tend to rise to figure on maps that are mostly light (e.g., with a white background), while map symbols that are light tend to rise to figure on maps that are mostly dark (e.g., with a black background).

7. *Texture* describes the coarseness of the fill pattern within the map symbol. It was once common to manipulate texture in choropleth maps using halftone or dithering techniques in order to mimic the appearance of shading; as described above, contemporary choropleth maps instead manipulate the visual variables associated with color due to advances in modern printing and digital display devices. Caivano (1990) describes texture as a higher-order visual dimension with three constituent components: the directionality of the texture units (related to the visual variable orientation), the size of the texture units (related to the visual variable size), and the density of the texture units (approaching the perceptual effect of shading associated with the visual variable color value). Regarding the latter component, map symbols with a denser texture tend to rise to figure.

Bertin's set of visual variables was extended by Morrison (1974) to include two additional variables used in cartographic design:

8. *Color saturation* describes the spectral peakedness of the map symbol across the visible spectrum, and is the third of three visual variables associated with the perception of color. Bold or saturated colors emit or reflect energy in a concentrated band of the visible spectrum, whereas pastel or desaturated colors emit or reflect energy evenly across the visible spectrum. From a design standpoint, therefore, color value can be conceptualized as the amount of black in a map symbol while color saturation can be conceptualized as the amount of grey in a map symbol. Color saturation also is referred to as 'chroma', 'intensity', and 'purity' in color theory. Bold, saturated map symbols tend to rise to figure while pastel, desaturated map symbols tend to recede to ground.

9. *Arrangement* describes the layout of graphic marks constituting a map symbol. The visual variable arrangement varies from regular (i.e., graphic marks are perfectly aligned in a grid-like structure) to irregular (i.e., graphic marks are randomly placed or coalesce into clusters). Arrangement differs from the visual variable texture in that all textures are assumed to be arranged regularly, regardless of the initial direction, size, and density of the texture. Dot density maps vary in both arrangement and texture density, a higher-order visual dimension described as 'numerousness' by Nelsen (2000). Map symbols with irregular, and particularly clustered, arrangements tend to rise to figure.

Finally, MacEachren (1995) identified three additional visual variables whose manipulation is made easier through digital production methods. MacEachren (1992) originally grouped these three visual variables under a single technique called 'focus' in context of uncertainty visualization, but ultimately acknowledged each component as a visual variable given the potential application to other forms of cartographic representation.

10. *Crispness* describes the sharpness of the boundary of the map symbol. Crispness also is referred to as 'depth-of-field' and 'fuzziness' in Information Visualization. MacEachren et al. (2012) found that crispness was the most effective visual variable for representing uncertainty in the context of point symbolization. Map symbols with a crisp boundary tend to rise to figure while map symbols with a fuzzy boundary tend to recede to ground.

11. *Resolution* describes the spatial precision at which the map symbol is displayed. The visual variable resolution relates to the topic of generalization in cartographic design, which describes the meaningful removal of detail in the map design as the complexity of the real world is abstracted to fit the reduced scale of the map. Resolution as a visual variable leverages different levels of abstraction to encode information, rather than the typical purpose of generalization. In a raster depiction, resolution refers to the coarseness of the grid size. In a vector depiction, resolution refers to the amount of detail (in terms of nodes and edges) in the linework. Map symbols that are depicted in a relatively high level of detail tend to rise to figure.

12. *Transparency* describes the amount of graphic blending between a map symbol and the background or underlying map symbols. MacEachren (1992) originally referred to transparency as 'fog' to suggest a partially opaque barrier impacting the clarity of the underlying map symbols. Transparency is the primary visual variable manipulated in

value-by-alpha maps (the 'alpha' channel indicating transparency in computer graphics), an alternative to the value-by-area cartogram that visually equalizes enumeration units by adjusting their opacity rather than their size (Roth et al., 2010). Opaque map symbols tend to rise to figure.

Perceptual Basis of the Visual Variables and their Syntactics for Mapping

An important characteristic of the visual variables is that they are processed preattentively, or in an immediate and preconceptual manner at the sensory level of the human eye. Accordingly, the direct translation of Bertin (1967|1983) is 'retinal' variable rather than 'visual' variable. Thus, the visual variables are 'seen' perceptually rather than 'understood' cognitively. Principles of perceptual psychology predict how each visual variable is processed by the eye-brain system, and therefore inform use of one visual variable over others for cartographic design. Bertin postulated four such ways that visual perception may inform application of the visual variables in maps and other visualizations, describing these four properties as 'levels of organization'.

Bertin's (1967|1983) first level of organization is *associative perception*. With an associative visual variable, variations in the visual dimension are perceived with equal weight, allowing for the eye to perceive all map symbols with the same variation as a group (i.e., as associated). For instance, the eye is not drawn to one color hue over the other in Figure 2a or one shape over another in Figure 2b, allowing for the perception of all map symbols having the same color hue or shape as an associated group; as a result, the eye is likely to see a series of horizontal rows in Figures 2a and 2b. Because no variation dominates, an associative visual variables allows the eye to attend visually to other visual variables that also might vary in the visual scene (see the below discussion on visual variable conjunctions and bivariate mapping). Bertin believed location, shape, orientation, color hue, and texture to be associative visual variables. With a dissociative visual variable, one variation dominates visual perception, with the eye drawn to this variation over others. In Figure 2c, the eye is drawn to the darker color values due to the contrasting white background, while in Figure 2d, the eye is drawn to the larger sizes. As a result, the eye perceives a vertical gradient in Figures 2c and 2d, rather than a set of horizontal rows as in Figures 2a and 2b, despite all four figures encoding the same information. Variation in a dissociative visual variable inhibits attention to other visual variables that may vary in the visual scene. Bertin believed size and color value to be dissociative visual variables.

[place Figure 2 approximately here]

Bertin's (1967|1983) second level of organization is *selective perception*. With a selective visual variable, the eye is able to focus individually (i.e., attend selectively) upon each variation of the visual variable across the visual scene and ignore the other variations. In other words, it is relatively easy to isolate visually the distribution of a particular category of map symbol across the map when symbolized using a selective visual variable. For example, it is easier to see the distribution of red symbols in Figure 2e than the distribution of hexagonal symbols in Figure 2f, despite the pair of figures encoding the same information. Bertin believed shape to be the only visual variable that was not selective. This property makes shape useful when each map symbol should be interpreted individually, such as in the context of large qualitative point symbol sets.

However, shape is not useful when scanning for broad patterns across all map symbols, an important goal of most thematic mapping.

Bertin's (1967|1983) third level of organization is *ordered perception*, while his fourth level of organization is *quantitative perception*. Variations in ordered visual variables are perceived as ranked, with the eye preattentively interpreting one variation as 'more' or 'less' than another variation. For example, the green symbols in Figure 2e are not perceived as 'more' than the purple symbols, just different. In contrast, the darker symbols in Figure 2g are perceived as 'more' than the lighter symbols, given the white background. Bertin believed location, size, color value, and texture to be ordered visual variables; MacEachren (1995) later argued that color saturation, crispness, resolution, and transparency also are strongly ordered visual variables and that texture is only marginally ordered. Quantitative perception extends ordered perception, allowing for the estimation of numerical values from variations in quantitative visual variables. For example, the darker symbols in Figure 2g are perceived as 'more' than lighter symbols, but it is difficult to estimate how much more without use of a legend. In contrast, it is possible to estimate how much 'more' the larger symbols in Figure 2h are than the smaller symbols. Bertin believed quantitative perception to be restricted to location and size only.

Importantly, Bertin's (1967|1983) third and fourth levels of organization inform MacEachren's (1995) visual variable *syntactics*. In semiotics, syntactics describes the relationship of sign vehicles to one another. In Cartography, syntactics prescribes the use of a visual variable given the level of measurement of the attribute information. Unordered visual variables—such as color hue, orientation, and shape—are appropriate for encoding nominal information. Visual variables that are ordered, but not quantitative—such as color value, color saturation, crispness, resolution, and transparency—are appropriate for encoding ordinal information. Finally, visual variables that are quantitative—such as location and size—are appropriate for encoding numerical information, but also can be applied for ordinal and nominal information given their visual dominance. Figure 1 reproduces MacEachren's visual variable syntactics, designating each visual variable as good, marginal, or poor for nominal, ordinal, and numerical levels of measurement.

Visual Variables Conjunctions and Bivariate Mapping

Maps or other visualizations can make use of a *conjunction* of two visual variables. Conjunctions can be applied for redundant symbolization, strengthening the graphic encoding of one attribute, or for representing multiple attributes in a bivariate display. For bivariate maps, a conjunction can be *homogeneous*, using the same visual variable in two different ways, or *heterogeneous*, using two different visual variables to represent the pair of attributes. In Cartography, this distinction also relates to the map symbol's dimensionality (point, line, polygon, and volume), with a homogenous conjunction manipulating the visual variables at the same symbol dimensionality and a heterogeneous conjunction manipulating the visual variables at different symbol dimensionalities. The images in Figure 3 encode the same pair of attributes, but Figure 3c represents them using a conjunction that is homogeneous, Figures 3a, 3b, and 3d using a conjunction that is heterogeneous by visual variable, and Figure 3a using a conjunction that is heterogeneous by symbol dimensionality.

[place Figure 3 approximately here]

As with individual visual variables, perceptual psychology informs the syntactics of visual variable conjunctions. The most promising work to-date is based on the sensory characteristic of selective attention, or the ability to attend to only one visual variable while ignoring others. Visual variable conjunctions exhibit one of four conditions of selectivity, each of which is appropriate for a different mapping context (Nelson, 2000).

First, a *separable conjunction* describes a bivariate map or visualization in which selective attention of both attribute encodings is uninhibited. With a separable conjunction, the distribution of each attribute ('X' and 'Y') can be 'seen' without one restricting the other. Separable conjunctions are produced when using the visual variable shape, given its status as the only non-selective visual variable. Conjunctions that are heterogeneous by symbol dimensionality also tend to be separable, meaning that a thematic combination of choropleth or isoline (i.e., areas) with dot density or proportional symbol (i.e., points) will result in a separable conjunction. In Figure 3a, it is easy to attend to the distribution of either attribute ('X' and 'Y'), but relatively difficult to determine their spatial correlation ('+'). A separable conjunction also is created when combining size and color value on the same symbol dimension, as both visual variables are dissociative; thus, shaded cartograms and shaded proportional symbol maps are considered separable. Elmer (2013) recommends use of a separable conjunction when mapping two independent variables that have incongruous scales (e.g., different units of measure, different methods of normalization, different classification breaks), as there is no assumed correlation and the user is forced to attend to each attribute scale individually.

The conceptual opposite of a separable conjunction is an *integral conjunction*. With integral conjunctions, selective attention is possible on an emergent—or *gestalt*—visual dimension ('+'), but selective attention of each original attribute encodings ('X' and 'Y') is inhibited. In this situation, it is easy to 'see' where the two attributes are the same or different on their respective scales, but it is difficult to attend to each attribute individually. Recommended color schemes for bivariate choropleth maps make use of an integral conjunction, with the arrangement of colors producing an emergent dimension of increased color value as both attributes increase. In Figure 3b, it is easy to determine where both attributes are high or low in tandem by attending to changes in color value ('+'). However, it is difficult to attend to only one attribute at a time; for instance, both New Mexico and Oregon have the same value in the 'X' variable, but this is not easily interpreted due to the integral conjunction. Elmer (2013) recommends use of an integral conjunction when the correlation between dependent attributes is more important than the attributes themselves, as the gestalt dimension will focus the user upon this correlation.

Separability and integrality represent ends of a continuum of conjunctive selectivity, with different conjunctions falling somewhere upon this continuum in terms of visual strength. A *configural conjunction* describes a situation falling in the middle of this continuum, where a gestalt dimension exists ('+'), but the original attribute encodings are not fully inhibited ('X' and 'Y'). Here, it is possible to attend to each attribute, but there also is a visual cue aiding interpretation of the correlation between the attributes. Homogenous conjunctions that make use of split symbols are likely to be configural, as they exhibit a gestalt dimension of being 'in-phase' (i.e., having the same value for each half of the symbol) or 'out-of-phase'. In Figure 3c, it is possible to attend to either side of the split graduated symbol ('X' and 'Y'), but also easy to interpret where both attributes are high (e.g., Utah) or low (e.g., Arizona) together, as the two halves reform the original circular shape. Elmer (2013) recommends use of a configural conjunction when mapping two independent attributes that have congruous scales, as the condition of being 'in-phase' implies the same attribute value on the same attribute scale.

Finally, an *asymmetrical conjunction* describes a situation in which a non-logical gestalt dimension emerges in addition to the positive correlation, as is the case with integral and configural conjunctions. Here, the non-logical emergent dimension (-) inhibits the ability to 'see' one of the two attributes ('X' or 'Y'), producing an imbalanced visual effect in which the reader tends to interpret one attribute over the other. Asymmetrical conjunctions tend to be produced when using size or color value with other visual variables, given their status as dissociative visual variables. An asymmetrical conjunction also is produced with a value-by-alpha map (Figure 3d), with the attribute encoded using color ('X') visually equalized by the attribute encoded using transparency ('Y'). Elmer (2013) recommends using an asymmetrical conjunction when one attribute (i.e., the variable of interest) is more important than the other (i.e., the equalizing variable).

The visual variables remain a central framework for empirical research on cartographic design, informing both the experimental trials and controls. A similar approach rooted in semiotics also has been taken to understand dynamic representation in animated maps (DiBiase et al., 1992), sonic representation in multimodal maps (Krygier, 1994), haptic representation for handheld devices (Griffin, 2002), and interactivity (Roth, 2012).

SEE ALSO: Cartographic Design, Choropleth Map, Color Theory, Representation and presentation, Visualization, Visualizing Uncertainty

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Further Readings

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Key Words

Cartography, visualization, mapping

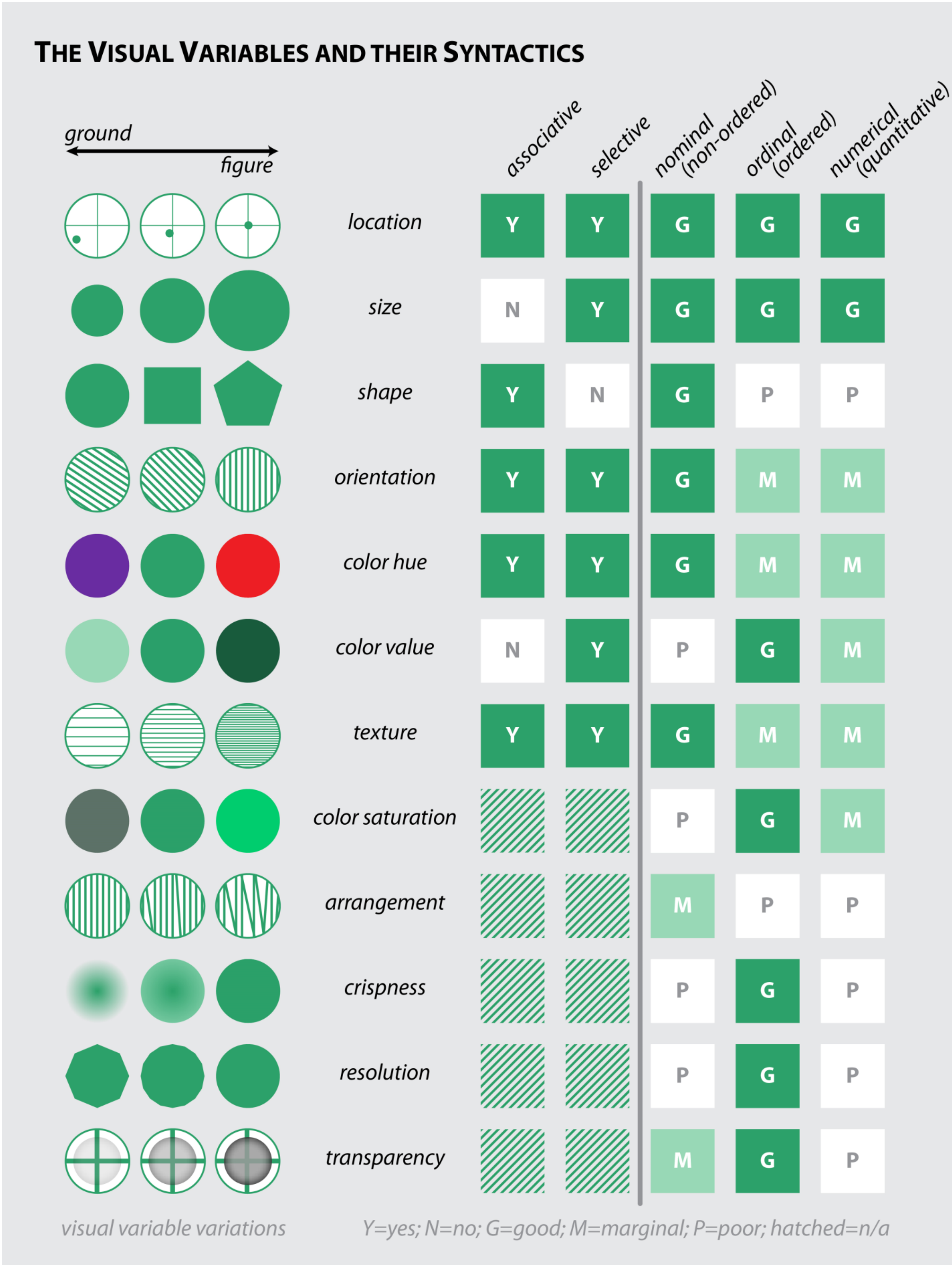

Figure 1: The Visual Variables and their Syntactics. Figure derived from Bertin (1967|1983), MacEachren (1995), and MacEachren et al. (2012).

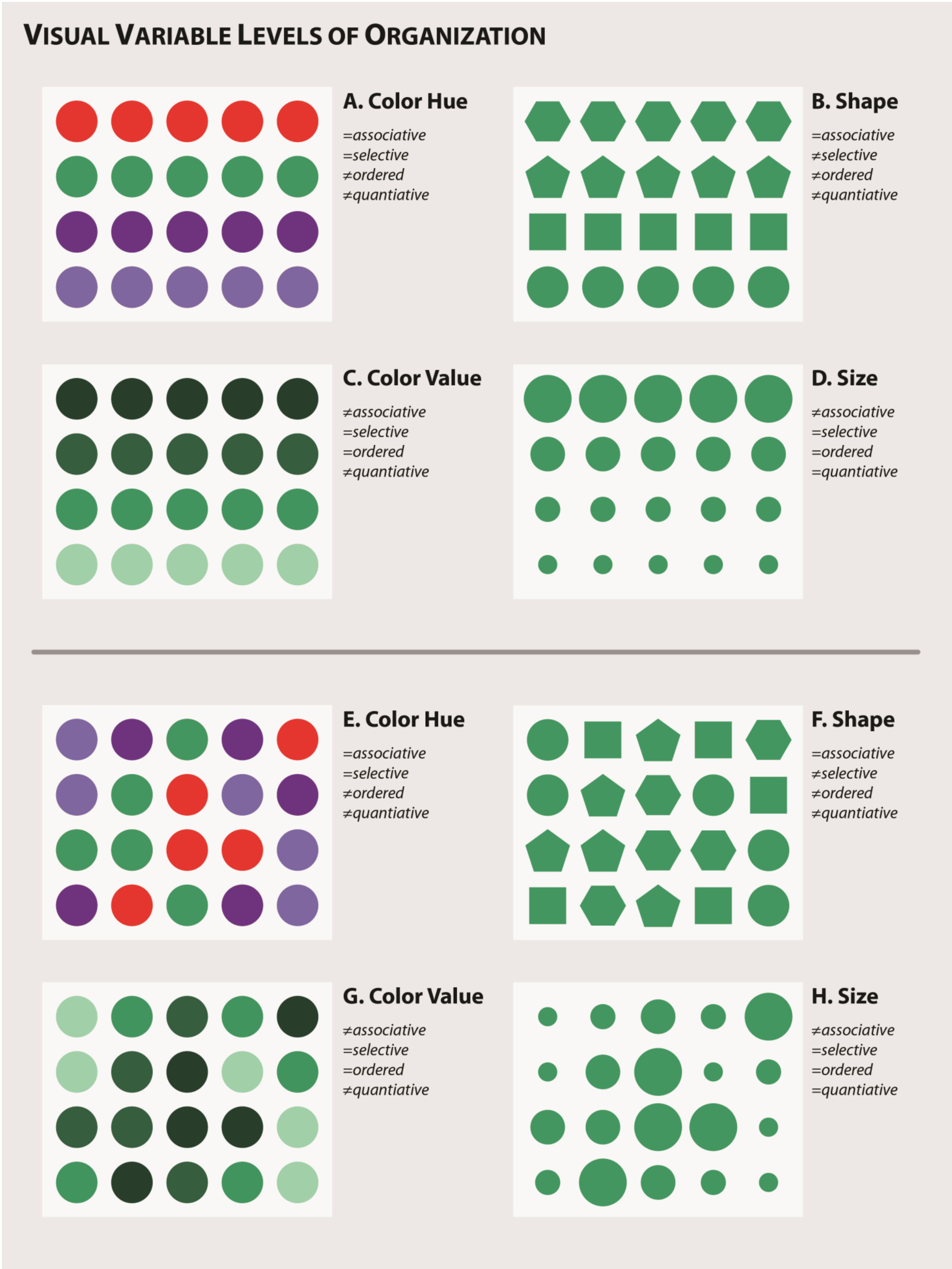

Figure 2: Visual Variable Levels of Organization. Figures A-D and E-H depict the same attribute information. Figure based on Bertin (1967|1983).

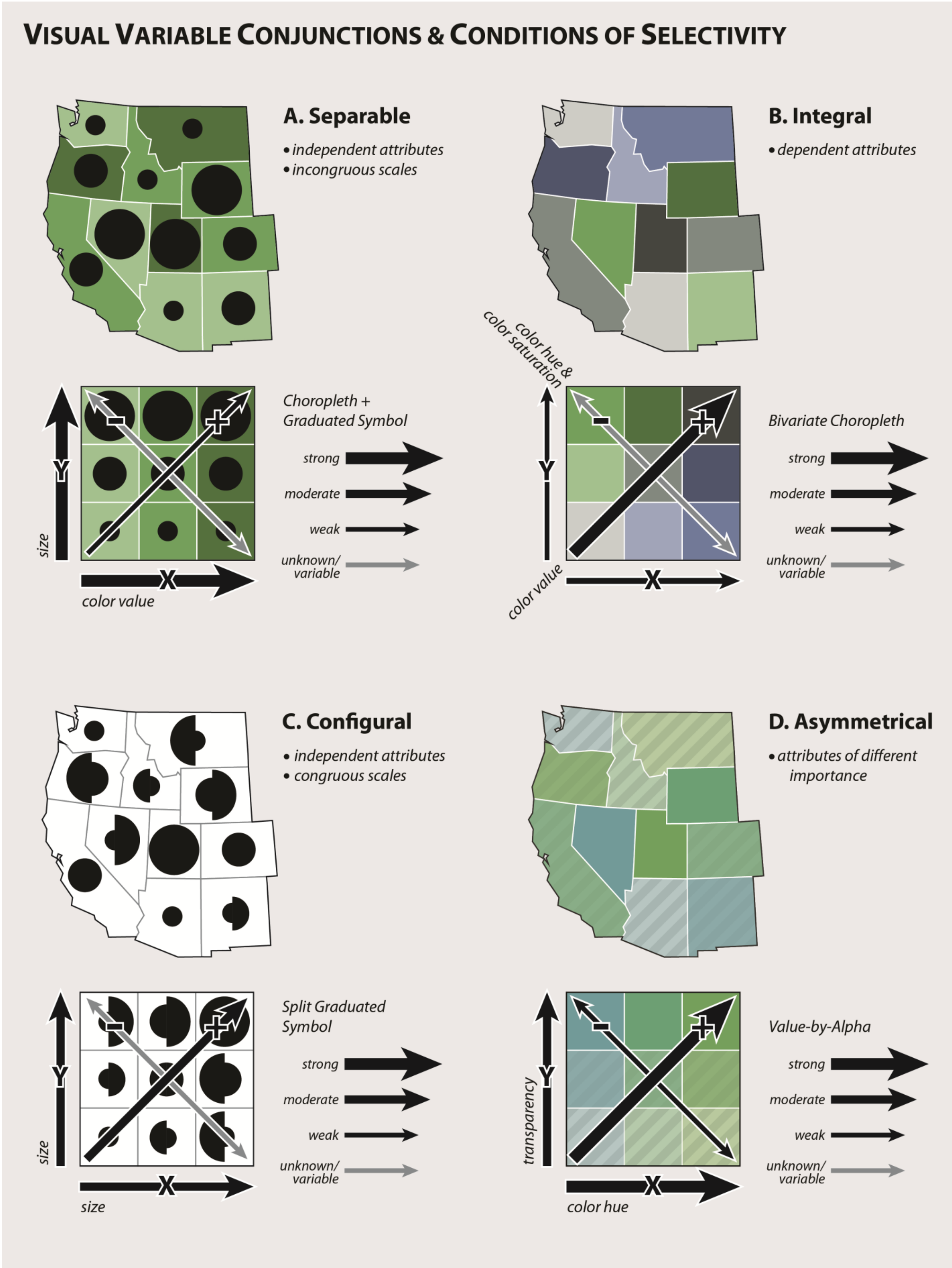

Figure 3: Visual Variable Conjunctions and Conditions of Selectivity. All maps depict the same attribute information. Figure derived from Elmer (2013).