Glyph-based Visualization: Foundations, Design Guidelines, Techniques and Applications

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Abstract

This state of the art report focuses on glyph-based visualization, a common form of visual design where a data set is depicted by a collection of visual objects referred to as glyphs. Its major strength is that patterns of multivariate data involving more than two attribute dimensions can often be more readily perceived in the context of a spatial relationship, whereas many techniques for spatial data such as direct volume rendering find difficult to depict with multivariate or multi-field data, and many techniques for non-spatial data such as parallel coordinates are less able to convey spatial relationships encoded in the data. This report fills several major gaps in the literature, drawing the link between the fundamental concepts in semiotics and the broad spectrum of glyph-based visualization, reviewing existing design guidelines and implementation techniques, and surveying the use of glyph-based visualization in many applications.

1. Introduction

Glyph-based visualization is a common form of visual design where a data set is depicted by a collection of visual objects referred to as *glyphs*. In a narrow interpretation,

- **(a.1)** a glyph is a small independent visual object that depicts attributes of a data record;
- **(a.2)** glyphs are discretely placed in a display space; and
- **(a.3)** glyphs are a type of *visual sign* but differ from other types of signs such as *icons*, *indices* and *symbols*.

In a broad interpretation,

- **(b.1)** a glyph is a small visual object that can be used independently and constructively to depict attributes of a data record or the composition of a set of data records;
- **(b.2)** each glyph can be placed independently from others, while in some cases, glyphs can be spatially connected to convey the topological relationships between data records or geometric continuity of the underlying data space; and
- **(b.3)** glyphs are a type of *visual sign* that can make use of visual features of other types of signs such as *icons*, *indices* and *symbols*.

In many applications, the spatial location of each glyph is pre-determined by the underlying spatial structure encoded in the data, such as a map in geo-information visualization, or a volumetric field in diffusion-tensor imaging. In other applications, the spatial location represents the result of a visual mapping from non-spatial information, such as the temporal dimension and semantic grouping of data records.

While glyphs are a form of illustrative graphics and visualization, fundamentally they are dictionary-based encoding schemes. Historically, many of such schemes (e.g., maritime semaphore and signal flags) have made indispensable contributions around the world. Technically, dictionary-based encoding has shown great merits in text compression and image compression. In the era of data deluge, one cannot help to contemplate the cost-effectiveness of using glyph-based visualization in many applications, and the long-term potential of evolving glyph-based encoding schemes into a common visualization language.

The design of glyphs can make use of many different *visual channels* such as shape, colour, texture, size, orientation, aspect ratio or curvature, enabling the depiction of multi-dimensional data attributes. Meanwhile, glyphs are normally recognisable individually, offering a means of visual fusion in multi-field visualization. Similar to most types of visual signs, a specific design of a glyph set is fundamentally a visual coding scheme. Like all coding schemes, a well-designed glyph-based visualization can facilitate efficient and effective information encoding and visual communication. As a type of sign, a glyph is a stimulus pattern that has meanings, which can potentially attract greater attention and stimulate more cognitive activity during visualization than other forms of visual design. In dealing with the ever-increasing problem of data deluge, it is a technique that is not to be overlooked.

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In the literature of visualization, there have been a few major surveys related to glyph-based visualization. The survey by Ward [War08] provides a technical framework for glyph-based visualization, covering aspects of visual mapping and layout methods, as well as addressing important issues such as bias in mapping and interpretation. Ropinski et al. [RP08, ROP11] present an in-depth survey on the use of glyph-based visualization for spatial multivariate medical data. Lie et al. [LKH09] describe a general pipeline for the glyph-based visualization of scientific data in 3D along with design guidelines such as the orthogonality of individual attribute mappings. Because glyphs are commonly used in vector field visualization, they have been discussed and compared with other forms of visualization in a collection of surveys on flow visualization [PVH*03, LHD*04, PL09]. However, there is a need to build on these surveys by taking a holistic overview of glyph-based visualization in terms of the fundamental concepts and theories, design guidelines, algorithms and techniques and applications. In particular, this survey is intended to address some noticeable gaps in the literature by:

- systematically examining the extensively rich collection of theories in semiotics, perception and cognition; and identifying their relevance to glyph-based visualization;
- categorizing the technical methods for glyph-based visualization in the scopes of both narrow and broad interpretations, opening up the design space for future technical advances; and
- surveying a large collection of applications where glyph-based visualization has already made an impact.

The survey is organized as follows: Section 2 examines the studies of signs in philosophy, language studies and psychology. We draw fundamental understanding from these studies in order to establish formal definitions of glyphs and ways for classifying them. Section 3 surveys formal design guidelines, mapping techniques and layout algorithms and rendering methods that have been used in practice. Section 4, examines a number of application areas where glyph-based visualization has been deployed. In particular, it describes the benefits brought by glyph-based visualization. Section 5 summarizes the findings that have emerged during the compilation of this survey and proposes new interesting research avenues.

2. History and Related Concepts

The term *glyph* is originated from Greek word, *glyphē*, meaning carving. Since the 16th century, its uses in English have been much associated with etymology, archaeology, topography and graphonomics. Although its contemporary use in the context of multivariate visualization may seem rather different, they share many interesting attributes, such as being "small", being "visual", having "meaning", requiring "learning", and often being "metaphoric". It is thus interesting to study briefly the related history and concepts.

2.1. A brief history of the study of signs

Signs in terms of indices, icons and symbols (Figure 1) are all different aspects of a similar unit of knowledge representation, which has been used as a fundamental concept in trade, commerce and industry from early days to present. Symbolism has played an important part in the development of human culture, especially as a form of communication. The Paleolithic Age, around 18,000 BC, has given us hundreds of examples in the form of cave paintings. The Neolithic Age instead provides the first forms of pre-writing symbols used for communication: the Petroglyphs, images incised in rock *petra* (meaning "stone") + *glyphein* (meaning "to carve") . Tribal societies continue to use this form of symbolic writing even in current times.

An interesting aspect of petroglyphs is their similarity across different continents; the commonality of styles strengthens the hypotheses that human conceptual system is symbolic in nature as investigated by Jungian psychology and early works from Mircea Eliade [EM91]. Psychophysical studies have demonstrated how recurrent geometric patterns (*form constants*) in petroglyphs and cave paintings are "hard-wired" into the human brain. Petroglyphs are ancestors to pictograms (or pictograph) symbolic representations restricted not just to objects but also places, activities and structured concepts. Ideograms (or ideograph) are graphical symbols analogous to pictograms but believed to have appeared later and with the main intent of representing "ideas"; contemporary examples of ideograms can be found in wayfinding signage as well as technical notations such as arabic numerals, mathematical notations or binary systems, which maintain the same meaning despite the difference in language and environment. Pictograms and ideograms are at the base of early written symbols such as cuneiforms and hieroglyphs to sophisticated logographic writing system such as the ones developed in Chinese and Eastern cultures. A logogram (or logograph) is defined as a "grapheme" the fundamental unit of a written language (as opposed to phoneme the fundamental unit of a spoken language). It can represent either a single letter or a morpheme, the smallest meaningful unit in the grammar of a language (e.g. a whole word or concept). The Cuneiform writing system for example, employed signs to represent numbers, things, words, and their phonetics. Egyptian hieroglyphs contained a combination of logographic, alphabetic, and ideographic elements, consisting mainly of three kinds of glyphs: phonetic glyphs, including single-consonant characters that functioned like an alphabet; logographs, representing morphemes, and ideograms, which narrowed down the meaning of a logographic or phonetic word. Chinese characters instead are derived directly from individual pictograms or combinations of pictograms and phonetic signs and represents logograms used in writing Chinese, Japanese and Korean.

Examples of pictograms can be easily found today. Interesting examples are the Pub and Inn signs found in Eng-

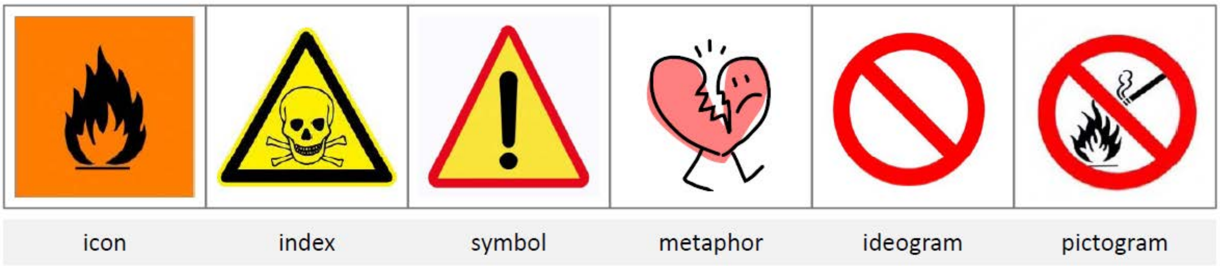


Figure 1: In philosophy, language studies and psychology, signs may take one of the three forms, icon, index and symbol. In many contexts, terms such as visual metaphor, ideogram and pictogram are also used to denote subclasses of signs.

land, Europe and North America. After an edict from King Richard II in 1393 that required all alehouses to post a sign they soon became a method of identifying and promoting themselves to the official ale tasters and the public. These signs still remain a tradition often exposing creative and unusual but always metaphoric. The use of symbols and signs has traversed human history for generations, due to their cross-cultural expressive power. Signs and symbols are fundamental means for communication transcending cultural boundaries. With the advent of the computer era, icons have become one of the most popular means of conveying messages. In the early 1980s the CHI community [BSG89, Bly82, Gay89] investigated the use of sounds in associations with visual display to create a new type of multisensory signs: the "earcons". Today the use of icons, with added sophisticated features such as animations and sounds, is now pervasive throughout most media platforms. As highlighted by Marcus [Mar03] specialised communities such as health and medicine, finance and banking, travel and transportation, and education and training, already possess widespread and sophisticated proprietary visual sign systems. The power of expression inherent to visual sign systems is appealing to media, technology and information visualization alike. The challenge relies on the development of well-designed sign systems.

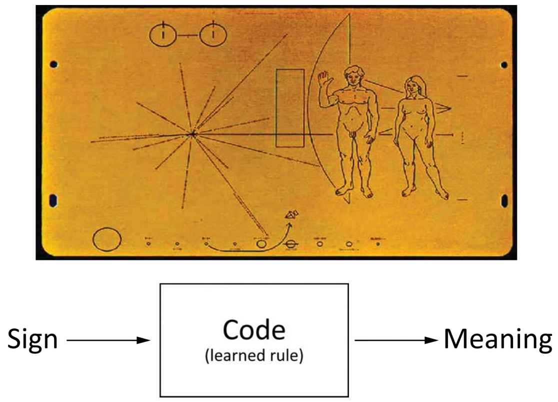


Figure 2: The Pioneer 10 Spacecraft 1972 Plaque.

2.2. Functional Space

According to Peirce [Pei02]'s theory of signs all modes of thinking depend on signs. Signs act as mediators between the external world of objects and the internal world of ideas. A sign in itself is a *stimulus pattern* associated with a *meaning*. Depending on *how* the meaning is associated with the pattern (or object) a sign can be classified as either an icon, an index or a symbol. The icon, index and symbol triad represents the different relationship between the sign and its object. Icons (such as pictures, images, models, or diagrams) represent a sign that itself resembles the qualities of the object it stands for (*physical correlation*). Indexes are defined by some sensory feature (such as a clock, thermometer, fuel gauge, or medical symptom) and therefore represent a sign which demonstrates the influence of its object (*space and time correlation*). Symbols (such as a trophy, medal, receipt, diploma, monument, word, phrase, or sentence) represent a sign which is interpreted as a reference to its object. For this reason, symbols are the only type of sign which do not require any physical, space or time correlation between the sign and its meaning (*metaphysical correlation*).

Codes provide the framework within which signs assume a meaning. A symbol, for example, is a sign where the function is a conventional rule (or coding) and is dependent only on a process of interpretation (Figure 2).

2.2.1. Icons

The functional domain of icons is comprised of: images, metaphors and diagrams. These three items all share topological similarity with the object they are related. Images share sensory qualities, diagrams share relational and structural qualities, while metaphors elicit the representative character of an object by building a parallelism with something else [JL02]. The typology of signs can be described based on the different ways a sign refers to its object [PB55]. Indices require the existence of the object they are a sign of, symbols require an interpreter; while icons require neither object nor interpreter. A Euclidean diagram for example, is made up of streaks of pencil lead that represent a geometric line even though the latter "has no existence" [Pei02].

2.2.2. Indices

The functional domain of indices is comprised of: tracks, symptoms and designations [JL02]. The three types of index represent abstractions that rely on a physical cause/effect relation which is not necessarily simultaneous with the object to which they relate to. Despite simultaneously not being a constraint, an index cannot be a sign without its object (e.g smoke is a symbol/sign of fire).

2.2.3. Symbols

The functional domain of symbols is comprised of all abstractions which rely on a code conventionally used in order to determine meaning. Examples of symbols are languages, mathematical symbols and alphanumeric characters on a computer keyboard. Symbols as signs need an interpreter but do not require any space or time correlation with the object they are a sign of, therefore a symbol represents the only type of sign which: a) can be easily removed from its context; and b) is closely associated with large sets of other words.

2.2.4. Codes

The Pioneer 10 plaque (Figure 2) represents an attempt at communication with alien beings via a "pictorial message" including all three type of signs previously described (e.g. icons, indices and symbols) and it is an exemplar testimony of the importance of what semioticians call codes. Coding is one of the fundamental concepts in semiotics and represents a deterministic functional relation between two sets of entities, namely: a signifier and a signified. Reading an image, like the reception of any other message, is dependent on prior knowledge of possibilities (signifier); we can only recognise what we know (signified). It is this information alone that enables us to separate the code from the message. Related to sign, it is possible to distinguish between three main kind of codes [Cha02]: social codes, textual codes and interpretative codes.

2.2.4.1. Social Codes. All semiotic codes can be broadly classified as social codes, however within our classification we refer to social code in their narrow sense concerning implicit or explicit social agreements and behaviours as in:

- verbal language: phonological, syntactical, lexical, prosodic and paralinguistic subcodes;
- bodily codes: bodily contact, proximity, physical orientation, appearance, facial expression, gaze, head nods, gestures and posture;
- commodity codes: fashion, clothing and cars;
- behavioural codes: protocols, rituals, role-playing and games.

2.2.4.2. Textual Codes. Next to social codes and interpretative codes, textual codes represent one of the majour groups of codes. According to Chandler's classification [Cha02], textual codes relate to our knowledge and often act as vehicles to represent reality (representational codes). Examples are:

- scientific codes: including mathematics;
- aesthetic codes: within the various expressive arts (poetry, drama, painting, sculpture, music) and currents (classicism, romanticism, realism);
- genre, rhetorical and stylistic codes: narrative (plot, character, action, dialogue, setting), exposition, argument and so on;
- mass media codes: photography, television, film, radio, newspaper and magazine codes, both technical and conventional (including format).

2.2.4.3. Interpretative Codes. Interpretative codes are perhaps the more interesting as they include:

- ideological codes: individualism, capitalism, liberalism, conservatism, feminism, materialism, consumerism and populism;
- perceptual codes: visual perception.

Perception forms an integral part of the interpretation process. As a semiotic code, perception involves the ability to decode a message presented in a representational form (e.g. a sign) and as such involves a learning process based on the influence of culture and context. In Section 3 we discuss design guidelines that can be taken into consideration to aid the creation of glyphs with attributes making best use of human perception.

A code is a system of syntactic, semantic and behavioural elements which must respond to three basic principles: coherence, homogeneity, and systematicity. In a communicational framework a code is significant if given a message, heterogeneous in nature, it assumes its specificity when transmitted *through* the code. In the context of visual representation the importance of proper coding is therefore self-explicative. Eco [Eco79] distinguishes between "signification" and "communication". Signification is seen as the semiotic event whereby a sign "stands for" something; communication instead is seen as the transmission of information from a source to a destination. In this context codes establish rules for systems of signification and communication is made possible by the existence of a code, or by a system of signification. Without a code or a system of signification, there is no set of rules to determine how the expression of signs is to be correlated with their content.

2.3. Theoretic Frameworks

Whilst semiotics is often encountered in the form of textual analysis, it also involves studying representations and the "reality" always involves representation. Semiosis was first proposed as a term by Charles Sanders Peirce and subsequently expanded by Eco [Eco79] to designate the process by which a culture produces signs and/or attributes specific

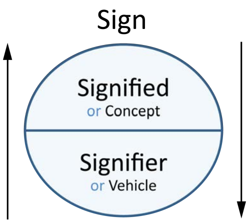


Figure 3: The Dyadic Model of the Sign Notion of Ferdinand de Saussure [SBSR83].

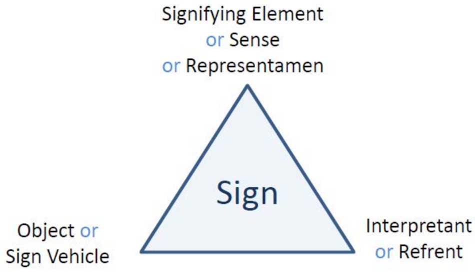


Figure 4: The Structure of the Sign Notion (Triadic Model) of Charles Sander Peirce [PB55].

meanings to signs. In modern semiotics there are two principal models of signs, the dyadic model due to Ferdinand de Saussure [SBSR83], and the triadic model due to Charles Peirce [PB55].

2.3.1. Semiotic Models: Diadic and Triadic

In the Dyadic Model (Figure 3) introduced by Ferdinand de Saussure [SBSR83] a sign is composed of the signifier (the sound pattern of a word, either in mental projection - as when we silently recite lines from a poem to ourselves - or in actual, physical realization as part of a speech act), and the signified (the concept or meaning of the word).

With its Triadic Model (Figure 4), Peirce [PB55] viewed the symbol/index/icon triad as "the most fundamental division of signs", and the majority of semioticians continue to agree [Joh88]. Peirce thus defines "semiosis" as the process by which representations of objects function as signs. Semiosis is a process of cooperation between signs, their objects, and their "interpretants" (i.e. their mental representations). "Semiotic" (i.e. the science of signs) is the study of semiosis and is an inquiry into the conditions which are necessary in order for representations of objects to function as signs.

2.3.2. Semiotic Systems: Algebra

According to Saussure [SBSR83] signs are always part of a formal system with a specific structure and relations. In its Semiotic Algebra Goguen [Gog03] devises a system to capture the systematic structure of a sign. In Semiotic Algebra a sign is always divisible into subparts called *sorts* (e.g., colour, location, size). Sorts may have a hierarchical structure with relationship such as inheritance or partial ordering between subsorts. Signs can be composed into more complex signs through constructor rules, functions that build new signs from other signs of given sorts plus additional parameters. Constructors express the whole/part relationship at the base of complex signs. Some sign constructors can be more important than others which gives rise to a priority partial ordering on the constructors of a given sort, for example: the pollutants in a lake may be prioritised by their toxicity, to aid in the design of an appropriate visualization. The complexity of a sign is measured in term of a hierarchy of levels, with atomic signs at the lowest levels and complex sign built from signs at lower or same levels.

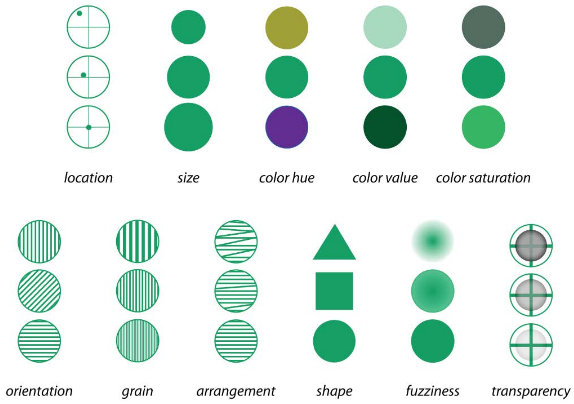


Figure 5: Visual Variables [Mac04].

2.3.3. Semiotic Systems: Grammar

Bertin [Ber83] proposed the first and probably unique attempt at developing a syntax of visual signs based on formal rules. Bertin identified six visual primitives, or fundamental visual variables, which are at the basis of the construction of any graphics sign: size, colour hue, colour value, grain, orientation, and shape. Bertin rated each visual variable in function of the signified dataset, giving a rating of appropriate or inappropriate to each visual variable for numerical, ordinal, and categorical data. This laid down the grammatical rules of a syntax to guide the choice of appropriate forms of graphical representation. MacEachren [Mac04] proposed adding three extra variables based on advances in graphics technology (Figure 5): clarity (fuzziness) of sign vehicle components, resolution (of boundaries and images), and transparency. He also provides a three-step rating for the full set of visual variables of good, marginal, and poor for use with numerical, ordinal, and categorical data. Mackinlay [Mac86] demonstrated the usefulness of such syntax of visual variables with his early implementation of an expert system for automating the design of graphical representations.

3. Design Criteria and Guidelines

Glyphs represent different data variables by a set of visual channels including shape, size, colour, orientation, etc. It was a wide-spread opinion in the related research community for a long time that "just" knowing these basic principles of glyph-based visualization would suffice to its successful usage. More recently, however, it has been understood that only well designed glyphs are actually useful. Visual channels such as colour [Chr75] or size [LMvW10] are more dominant and can help to focus the user's attention. Other channels such as position, length, angle or slope can be measured and compared more accurately [CM84a, HBE96]. An effective glyph visualization should, therefore, carefully choose and combine different visual channels. In this section, we discuss critical design aspects and guidelines for glyph-based visualization.

3.1. Design Space

As stated by Pettersson [Pet10] the main goal in information design is clarity of communication; in order to fulfill this goal, all messages must be accurately designed, produced and distributed, and later correctly interpreted and understood by members of the intended audience. Several principles to assist this design process have been proposed in the literature some empirical in nature others more formally defined.

3.1.1. Perceptual Codes

Gestalt psychologists outlined several fundamental and universal principles (or laws) of perceptual organisation which are assumed as a basis of a perceptual code (Figure 6): proximity, similarity, continuity, closure, figure/ground, area, symmetry and prägnanz.

The proximity principle (Figure 6a) states that objects that are closer to one another are perceived to be more related than those that are spaced farther apart. The proximity relation has been proved to be stronger than colour similarity.

The similarity principle (Figure 6b) states that objects that are similar are perceived to be more related than those that are dissimilar.

The continuity principle (Figure 6c) states that elements that are arranged on a line or curve are perceived to be more related than elements not on the line or curve. Continuation is stronger than similarity of colour.

The closure principle (Figure 6d) states that elements in a complex arrangement tend to be grouped into a single, recognisable pattern.

The symmetry principle (Figure 6e) states that objects are perceived as symmetrical shapes that form around their center. In Figure 6e (i) the perceived picture is usually three sets of opening and closing brackets while in Figure 6e (ii) the dominant picture would be two overlapping diamonds. In the first case symmetrical balance is stronger than proximity while in the second case symmetrical regions tend to be seen as the dominant figures.

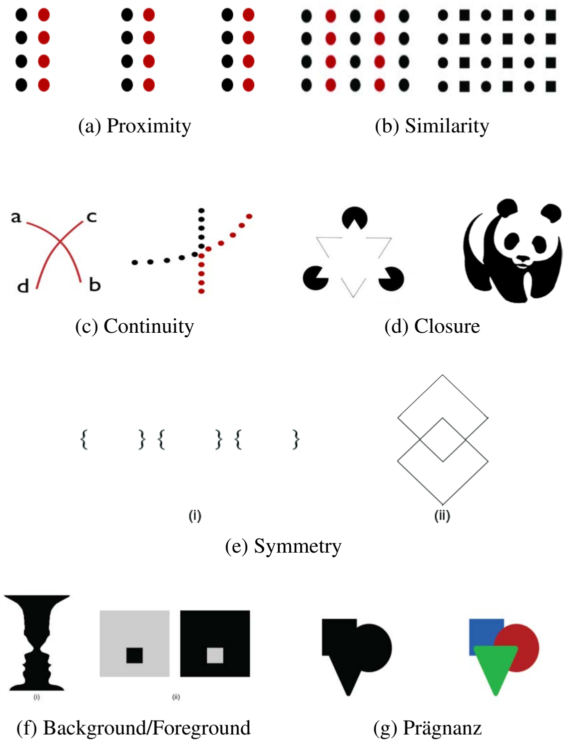


Figure 6: Gestalt Principles of Perceptual Organisation.

The figure/ground principle (Figure 6f) states that elements are perceived as either figure (element of focus) or ground (background or surrounding area). In this principle several factors play an important role: surroundedness, size (or area), symmetry, parallelism, and extremal edges. Each of these five properties can determine which parts of a figure are classified as figure or as background.

The prägnanz principle (Figure 6g) states that confronted with an ambiguous or complex representation the simplest and most stable interpretation is always favoured.

3.1.2. Visual Channels

A *visual channel* is a collection of primitive visual representations that are used to convey different values of a variable. Other terms were introduced in the literature. For example, Bertin called them *retinal variables*, Ware referred to them as *visual encoding variables* as well as *visual channels*. Cleveland and McGill proposed a ranking of several

Geometric Channels	Optical Channels	Topological and Relational Channels	Semantic Channels
• size / length / width / depth / area / volume • orientation / slope • angle • shape • curvature • smoothness	• intensity / brightness • colour / hue / saturation • opacity / transparency • texture (partly geometric) • line styles (partly geometric) • focus / blur / fading • shading and lighting effects • shadow • depth (implicit / explicit cues) • implicit motion / motion blur • explicit motion / animation / flicker	• spatial location • connection • node / internal node / terminator • intersection / overlap • depth ordering / partial occlusion • closure / containment • distance / density	• number • text • symbol / ideogram • sign / icon / logo / glyph / pictogram • isotype

Table 1: Visual Channels [CF12].

visual channels (i.e., position, length, angle, slope, area, volume, colour and density) [CM84b]. Mackinlay extended this exercise to some 13 visual channels [Mac86]. In addition, perceptual studies have been carried out to evaluate the effectiveness of some basic visual channels, resulting in a common consensus about pop-out effects of some of them : colour $\prec$ size $\prec$ shape $\prec$ orientation (e.g., [Wil67, QH87, ROP11]). The symbol $\prec$ reads as *precedes*. However, the strength of colour over the other three channels is generally much more noticeable.

Recently Chen and Floridi organised over 30 visual channels into a simple taxonomy consisting of four categories, namely geometric, optical, topological and semantic channels [CF12].

Combining these into a common table, we have a rich collection of visual channels (Table 1).

Most of these visual channels can be of potential use in glyph design, though only a small number of channels have been used in the literature. This suggests that the design space for glyphs is far from being fully explored.

3.1.3. Design Criteria

According to Eco [Eco79], a general semiotic theory should include not only a theory of how codes may establish rules for systems of signification but a theory of how signs may be produced and interpreted to clarify aspects of communications. In the work of Yousef [You01] five criteria have been proposed and empirically validated in the context of visual metaphors used in interface design. The criteria proposed are referred to with the acronym of CARSE: contextual suitability, applicability of structure, representability/imagery, salience imbalance, prominence and emotional tone.

Context suitability, or relevance, indicates the extent to which the metaphorical sign resembles the source domain with respect to the context of use.

Applicability of structure indicates the extent to which the proposed metaphorical sign is relevant to the new and unfamiliar concept that is being explained. The criteria can be regarded as the correspondence between the source and the target domain, in [TS82] is referred to as "Within-Domain Distance" while Lakoff [Lak95] calls it the "Invariance Principle".

Representability/imagery indicates the ease with which the visual metaphor can be represented.

Salience imbalance refers to Ortony's [Ort93] statement that good metaphors are the ones in which the source (vehicle) domain contains elements or traits, which are highly explicit/prominent; at the same time these traits are very subtle in the target (topic) domain. The visual representation should convey these salient source traits to the receiver.

Emotional tone indicates the importance of emotions triggered by the metaphor as one indicator of the semantic efficacy of the function that is presented metaphorically. In a recent study, Maguire et al. proposed a set of guidelines based on the literature of psychology and Bertin's categorisation of semantic relevance [MRSS*12]. These guidelines are:

- **Guideline on Semantic Relevance**. Bertin [Ber83] classified visual channels (which he referred to as retinal variables) into two categories, planar (location) and retinal (size, colour, shape, orientation, texture and brightness). Bertin proposed four semantic criteria for determining the suitability of different channels in representing certain types of information. These semantic criteria are: *associative*, *selective*, *ordered* and *quantitative*. Since then, research has also improved Bertin's analysis. For example, it was shown that practice and familiarity can support selectivity with almost any shape [TG88,WCG94,Gre98].
- **Guideline on Channel Composition**. As a glyph is likely to feature a number of visual channels, the constructive composition may affect how individual channels are perceived. A rich collection of literature on integral and separable dimensions shows that the combined dissimilarity of closely integrated visual channels exhibits Euclidean distance $\sqrt{d_a^2+d_b^2}$ [KT75, HI72], whereas that of separable visual channels exhibits city-block distance d_a+d_b [BSMWE78,She64]. The latter is more cost-effective than the former in rule-based encoding of multi-faceted concepts, therefore effective glyph design should encompass a non-conflicting set of separable retinal variables.
- **Guideline on Pop-out Effects**. Many classic studies in perception also established the "power" of different visual channels in terms of *pop-out effect* (pre-attentive search), and fixation (during attentive search) [HE11]. The *pop-out effect* is one which allows identification of a target within a few nanoseconds of initial exposure to the visual search space. A result of several milestone studies focusing on observed response times it shows the ordering of the four commonly used visual channels to follow the consensus: colour $\prec$ size $\prec$ shape $\prec$ orientation (e.g., [Wil67,QH87,ROP11]). The symbol $\prec$ reads as *precedes*. However, the strength of colour over the other three channels is generally much more noticeable.
- **Guideline on Visual Hierarchy**. *Visual hierarchy*, with which the environment and objects around us are arranged is a well documented theoretical framework [Pal77, Nav77, LRW99, KW79, Bar04]. However, the literature debates over the ways in which the visual system traverses this hierarchy. There are four possible ways: top-down (also called global processing) [Nav77]; bottom-up (also called local processing); middle-out [KW79]; and salient features (*e.g., edges, points, colours*) [Rum70]. Because glyphs are relatively small in comparison with an entire visualization, top-down and salient feature detection play significant roles in selecting a glyph or glyphs of interest. The top-down assumption suggests that when considering a glyph in isolation, its global features will affect visual search more than its local features. Salient features are partly addressed by pop-out effects.

In addition, Maguire et al. also suggested the importance of establishing a metaphoric association between a visual channel and the concept or concepts to be encoded [MRSS*12]. Metaphoric visual representations enable domain-specific encoding using "natural mapping" [Sii02, Nor02]. This natural mapping can make it easier for users to infer meaning from the glyph with less effort required to learn and remember them [MdBC00]. A recent study showed that visual metaphors can aid memorization of the information depicted in a visualization [BARM*12]. However, the same study also showed that visually realistic metaphors (those with a lot of detail) may have a negative impact on performance in visual search. Moreover, realistic visual metaphors require a higher pixel resolution, and would lose their discriminating capacity in low resolution visualizations.

A glyph is composed by a set of visual channels, each of which encodes a variable of a multivariate data record. Naturally the first criterion is that the visual channel should ideally be able to encode many valid values of that variable, or collectively, different visual channels of the glyph could encode many data records with different combinations of data values. However, this is not the only criterion, and in many cases, it may not even be the most important criterion. If the goal is to encode as many values as possible, one may be better off reading these values in text directly. Chung et al. [CLP*13] proposed eight criteria for glyph design in the context of sorting glyphs visually (Figure 7). These are:

a *Typedness* – This criterion refers to whether or not each visual channel in a glyph is appropriately selected to match with the data type of the variable to be encoded. Such data types may include, but not limited to: *nominal*, *ordinal*, *interval*, *ratio*, and *directional*.

b *Visual Orderability* – When a variable to be encoded is orderable, the corresponding visual channel should ideally be orderable visually (e.g., size, greyscale intensity, but not an arbitrary set of shapes).

c *Channel Capacity* – This refers to the number of values that may be encoded by a visual channel. Such a number is often affected by the size of a glyph and many perceptual factors (e.g., just-noticeable-difference, interference from nearby visual objects).

d *Separability* – When two or more visual channels are integrated into a compound channel, such as combining intensity, hue and saturation into a colour channel, the interference between different primitive channels should be minimised.

e *Searchability* – This refers to the levels of ease when one needs to identify a specific visual channel within a glyph for a specific variable.

f *Learnability* – This is often an important criterion in many applications. Ideally, a glyph design should be easy to learn, and easy to remember. There are many factors that may affect a visual design in this context, for instance, whether there are well-defined constructive rules, whether

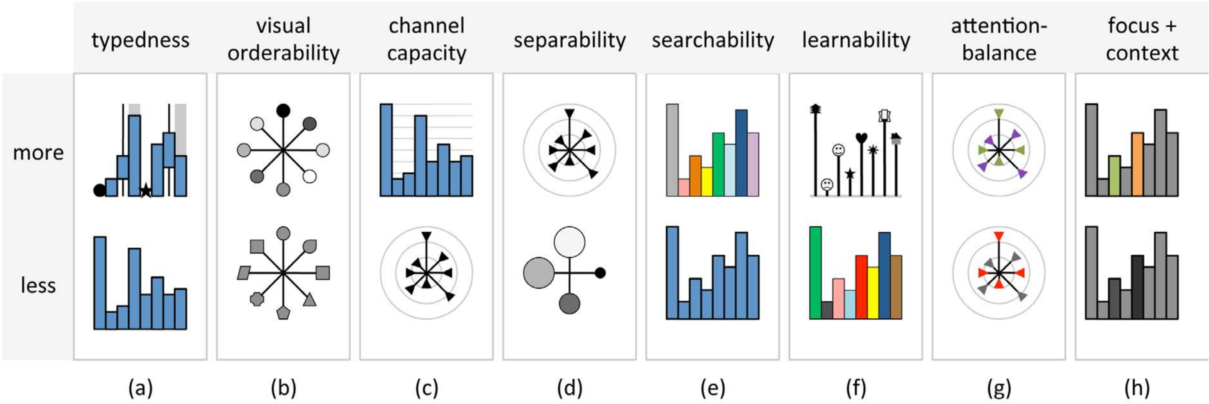


Figure 7: Glyph design criteria [CLP*13].

there are memorable metaphors, whether it is easy to guess, and so on.

g *Attention Balance* – Different visual channels in a glyph will receive different levels of attention. Ideally, the levels of attention should correspond to the levels of importance of the variables. However, this is easier said than done as the relative importance of a variable is often undefined or may vary from tasks to tasks.

h *Focus and Context* – This refers to the need to identify an individual visual channel under a certain interactive operation. For example, when a user select a certain variable as a sort key, it is desirable to highlight the corresponding visual channel so it stands out from other channels.

This is not an exhaustive list, and there are other design criteria, such as aesthetic appearance that also play an important role.

3.1.4. Design Processes

Petterson [Pet10] introduces four categories of principles supporting the visual representation design process:

- Functional Principles: focus, structure, clarity, simplicity, emphasis and unity;
- Administrative Principles: accessibility, cost, ethics and quality;
- Aesthetic Principles: harmony and aesthetic proportion;
- Cognitive Principles: facilitating attention, facilitating perception, facilitating mental processing and facilitating memory.

For each category Petterson provides detailed guidelines on how to achieve the target result with the appropriate use of text, picture, layout and colour.

Given the abundance of multivariate data, perceptual and cognitive efficiency is at the core of glyph-based visualization. Karve and Gleicher [KG07] identify three considerations for the design of complex and compound glyphs: integral-separable dimension pairs, natural mappings and perceptual efficient encoding. Integral-separable dimension pairs focus on the readability of multi-attribute glyphs and multi-glyphs displays, Karve and Gleicher [KG07] argue that individual glyphs should combine as many separable visual attributes as possible and multi-glyph displays should be dense, juxtaposing related items, and employing repetitive design motifs that support inter-glyph comparison. Natural mappings (e.g. use of metaphoric representations) focuses on the natural relationship between data and glyph features; a clear relationship between visual and data attributes enhances glyph usability. Perceptual efficiency of the encoding focuses on the encoding of a continuous variable; horizontal bars on a shared positional scale are found to be the most accurate method followed in decreasing order of accuracy by interval length, slope, area, volume, and colour.

3.1.4.1. Measurements and Norms If symbol design is to progress, we need to know more about why some symbols are easier to use than others. A major obstacle facing researchers attempting to answer this question has been the difficulties in quantifying symbol characteristics so that they can be experimentally controlled. A good way of controlling symbol characteristics experimentally is to obtain subjective ratings of each characteristic.

Although there has been a long tradition in psycholinguistic research of using normative ratings to control item characteristics for words and pictures, no normative ratings for symbols have yet been produced. McDougall et al. [MCdB99, MdBC00] address the problem by providing normative ratings for five symbol characteristics considered determinant in the development of easy to use and understand symbols: concreteness, visual complexity, meaningfulness, familiarity, semantic distance.

McDougall et al. highlights and investigates several interesting correlations between these five criteria. Concreteness, for example, (as opposed to abstraction) is somehow in opposition to visual complexity; concrete symbols tend to be more visually obvious because they depict objects, places, and people that are already familiar. In contrast, abstract symbols represent information using graphic features such as shapes, arrows and so on. One of the reasons why concrete symbols are more visually obvious may simply be because the extra detail provided in concrete symbols makes them easier to comprehend. In contrast, however, design guidelines typically suggest that the design of symbols or icons should be kept as simple as possible. Other researchers have focused on the fact that concrete symbols are more meaningful than abstract symbols.

Semantic, or articulatory, distance is a measure of the closeness of the relationship between the symbol and what it is intended to represent. A number of classification systems have been developed in order to attempt to characterise the different relationships between symbols and their functions [Pei02].

Familiarity reflects the frequency with which symbols are encountered. This property is thought to be an important determinant of usability. It is evident that user performance improves dramatically as a result of learning symbols and signs. The effects of some symbol characteristics on performance, such as colour and concreteness, diminish as symbols become more familiar but others, such as complexity, do not.

In [MdBC00, NC08] the relationship between: concreteness/visual complexity, concreteness/meaningfulness and meaningfulness/familiarity/semantic distance were examined in detail using subjective rating methods. For each characteristic subjects had to choose bipolar adjectives based on a five-point scale to indicate their perception of an icon. Ng et al. [NC08] propose a review of the relationships among the same five characteristics together with a description of three types of measures used in literature to quantify such relationships:

- subjective rating (as in [MdBC00]);
- icon-based metric: the measure is obtained summing up the components of an icon, such as letters, lines, arrows and so on;
- automated visual measurement: the measure is a function of icon features extracted via image analysis techniques such as edge-detection, perimeter determination, decomposition and so on.

Other symbol characteristics present in literature are discriminability, distinctiveness and configurality, however to provide a normative rating is a much harder task since such characteristics can only be defined (and quantified) in relation to the other symbols included in the display as a whole [MdBC00].

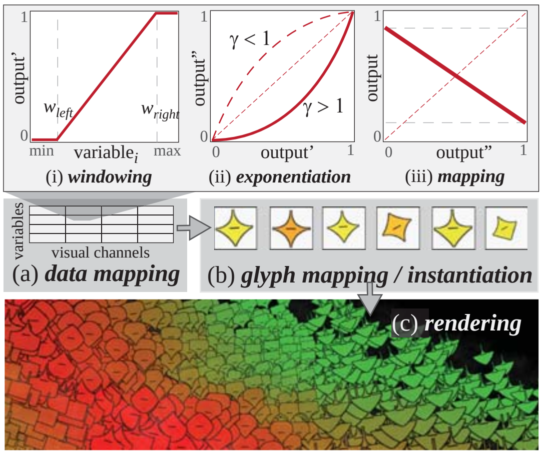


Figure 8: A pipeline for creating glyphs [LKH09]: (a) Each data variable is subject to three stages of data mapping: windowing, exponentiation and mapping. (b) The data variables are mapped to the different visual channels of a glyph (e.g., upper/lower shape, size, and rotation) and used to instantiate the individual glyphs. (c) Finally, the glyphs are rendered in their spatial context.

3.2. General Design Considerations and Guidelines

3.3. Design and Usage Guidelines for Glyphs

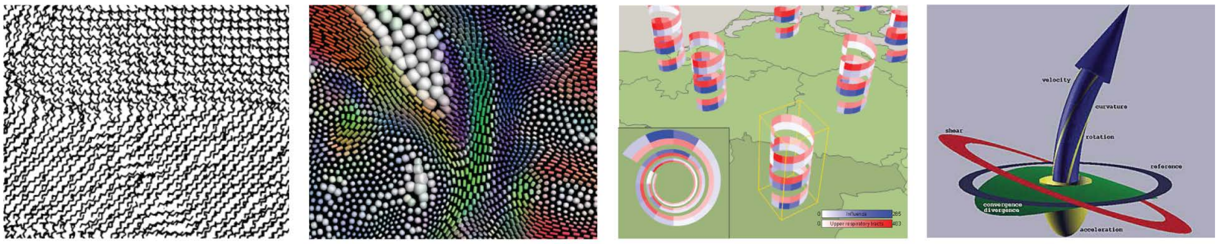
A number of design guidelines (marked with DGx in the following) for glyph-based visualization have been proposed [War02, War08, RP08, LKH09, ROP11, MRSS*12], and we review them in the following. Ward [War02] surveys glyph-based representations for information visualization and presents a taxonomy for glyph placement. Ropinski et al. [RP08, ROP11] propose a perception-based glyph taxonomy for medical visualization. Glyph-based visualizations are categorised according to:

- *pre-attentive* visual stimuli such as glyph shape, colour and placement, and
- *attentive* visual processing, which is mainly related to the interactive exploration phase (e.g., changing the position or parameter mapping of a glyph).

In the context of medical visualization, the authors propose usage guidelines for glyphs, which are addressed later on.

Inspired by the work of Ropinski and Preim [RP08], Lie et al. [LKH09] propose further guidelines for glyph-based 3D data visualization. Aligned with the visualization pipeline [HS09], the task of creating a glyph-based 3D visualization is divided into three stages as shown in Figure 8:

- during *data mapping*, the data attributes of a record are remapped (to achieve, for example, some contrast enhancement) and mapped to the different visual channels of a glyph;



(a) (b) (c) (d)

Figure 9: Small simple glyphs vs. large and complex glyphs: (a) Stick figures form textural patterns [PG88]. (b) Dense glyph packing for diffusion tensor data [KW06]. (c) Helix glyphs on maps for analyzing cyclic temporal patterns for two diseases [TSWS05]. (d) The local flow probe can simultaneously depict a multitude of different variables [dLvW93].

- *glyph mapping* (or glyph instantiation) creates the individual glyphs, properly arranged across the domain; and
- during *rendering*, the glyphs are placed in the resulting image, where one has to cope with issues such as visual cluttering or occlusion.

For each of these steps, the following sections discuss critical design aspects and guidelines for glyph-based visualization.

Table 2 illustrates different papers which are consistent with the design guidelines presented here. The papers are also categorised according to the utilised visual channels, dimensionality of the visualization space, and density of glyph placement.

[DG1] Task-based choice of visualization space. Glyph-based visualization approaches vary with respect to whether they are constructed in a 2D or 3D visualization space. In case of abstract data such as census or financial data, this decision is often dependent on the task at hand. However, certain scenarios with 3D volumetric or flow data inherently require a 3D visualization. We think that it also makes sense to consider glyph-based visualizations, which are based on the placement of glyphs on 3D surfaces [RSMS*07] (called 2.5D in the following).

[DG2] Task-based compromise between complexity and density. Glyph-based visualization approaches span a certain spectrum from dense arrangements of relatively simple shapes such as stick figures [PG88] (Figure 9a) to individual instances of complex glyphs that reveal a lot of information (but only for few, selected places, Figures 9c and d). Additionally, we can differentiate visualization solutions according to which visual channels are varied according to the data, and how many different values a glyph eventually represents. Usually this number is not too large, often 2 to 4, but then also examples exist where dozens of values are represented (e.g., the local flow probe [dLvW93] in Figure 9d).

[DG3] Hybrid visualizations. Ropinski et al. [RP08] suggest combining glyphs with other visualization techniques such as isosurfaces or volume rendering, which provide spatial context [RSMS*07, CM93]. When glyphs are not placed in a dense way, the space between them can be used for additional information. Treinish [Tre99], for example, visualizes multivariate weather data using colour contouring on vertical slices and isosurfaces that represent cloud boundaries. At user-defined locations (vertical profiles), the wind velocity and direction are represented by a set of arrow glyphs. Streamlines following the wind direction are seeded at each arrow. Kirby et al. [KML99] use concepts from painting for visualizing 2D flow. They combine different image layers with glyphs, elongated ellipses, and colour.

3.4. Data Mapping

Each dimension or variable of a data set will map to a specific graphical attribute. By modifying the order of dimensions while preserving the type of mapping, as many as N! alternate "views" of the data can be generated. An important issue in using glyphs is to ascertain which ordering(s) will be most supportive of the task at hand. Several possibilities exist, beyond random ordering or the order in which the variables were originally stored [War08]:

- **Correlation-driven.** Many researchers have proposed using correlation and other similarity measures to order dimensions for improved visualization [Ber83, ABK98, FK03, BS92]. These orderings help reveal clusters of similar variables, outlier records, and gradual shifts in relationships between variables.
- **Complexity and Symmetry-driven.** Gestalt principles indicate we have a preference for simple shapes, and we are good at seeing and remembering symmetry. In [PWR04] the shapes of star glyphs resulting from using different dimension orders were evaluated for two attributes: monotonicity (the direction of change is constant) and symmetry (similar ray lengths on opposite sides of the glyph). The ordering that maximised the number of simple and symmetric shapes was chosen as the best. User studies showed improved performance with complexity and symmetry optimised orderings.
- **Data-driven.** Another option is to base the order of the dimensions on the values of a single record (base), using

Figure 10: The figure shows monetary exchange rates over 3 years using random ordering.

Figure 11: In this figure, the dimensions are sorted based on the first record. Gradual changes and anomalies are much easier to perceive.

an ascending or descending sort of the values to specify the global dimension order. This can allow users to see similarities and differences between the base record and all other records. For example, sorting the exchange rates of 10 countries with the U.S. by their relative values in the first year of the time series exposes a number of interesting trends, anomalies, and periods of relative stability and instability (Figures 10 and 11).

- **User-driven.** As a final strategy, we can allow users to apply knowledge of the data set to order and group dimensions by many aspects, including derivative relations, semantic similarity, and importance. Derivative relations mean that the user is aware that one or more dimensions may simply be derived through combinations of other dimensions. Semantic similarity indicates dimensions that have related meanings within the domain.

Finally, some dimensions are likely to have more importance than others for a given task, and thus ordering or assigning such dimensions to more visually prominent features of the glyph will likely have a positive impact on task performance. In order to optimally represent a data variable using a visual channel of the glyph, the corresponding data range should be normalised, for instance, to the unit interval [ROP11, War02, LKH09]. The remapped data attributes parameterize the visual appearance of a glyph. Ropinski et al. [RSMS*07], for example, use an interface similar to a transfer function editor for mapping a data attribute to a visual channel of the glyph.

Lie et al. [LKH09] propose three consecutive steps for the data mapping stage. First, the data values within a user-selected data range $[w_{left}, w_{right}]$ are mapped to the unit interval (Figure 8a (i)). Values outside this range are clamped to 0 or 1, respectively. Consequently, the contrast of the visualization can be enhanced with respect to a range of interest (sometimes called *windowing*). A linear mapping would be a natural choice for this step, but also other forms of mapping could be considered, such as a discontinuous mapping. Another option would be a ranking-based mapping where the data is sorted first and each discrete value (or bin) is then shown differently, for example, using different shapes such as a triangle, circle, or star [STH02]. After the windowing, the contrast of a data variable can be further enhanced using an optional exponential mapping $e(x) = x^{\gamma}$. Using a value $\gamma \in]0,1[$, smaller values are represented more prominently (see the dashed red curve in Figure 8a (ii)). In contrast, larger values are emphasised with $\gamma > 1$. Since an exponential mapping can be hard to interpret, it should not be used as a default mapping. It can rather be applied when the user is interactively exploring the visualization, for instance, by modifying the parameter mappings to focus of different portions of the data. Finally, a third mapping step enables the user to restrict or transform the output range that should be depicted by a visual channel. Using a reverted mapping, for instance, smaller values, which are possibly more important to the user, are depicted in an enhanced style while larger values are de-emphasised. Consequently, also semantics of the data variables can be considered, which is an important guideline when mapping a data variable to a visual channel of a glyph [War02, ROP11].

3.5. Glyph Mapping / Instantiation

During glyph mapping the individual glyphs are created by representing the data variables with different visual channels of a glyph. During this step, the glyphs are also properly arranged across the domain. In the following, we discuss general design guidelines during this mapping stage as well as guidelines related to glyph shape and appearance.

[DG4] Perceptually uniform glyph properties. When mapping a data variable to a glyph property, equal distances in data space should be perceived equally as well. This is an important guideline for glyph design, and it was originally developed for colour maps [RTB96]. The box plot [MTL78], for example, uses position and height of the box / whiskers

Authors / Technique	design guideline													visual channel					
	[DG1] visualization space	[DG2] complexity vs. density	[DG3] hybrid visualizations	[DG4] perceptually uniform properties	[DG5] redundant mapping	[DG6] importance-based mapping	[DG7] view point independence	[DG8] simplicity and symmetry	[DG9] orthogonality and normalization	[DG10] intuitive / semantical mapping	[DG11] balanced glyph placement	[DG12] facilitate 3D depth perception	[DG13] interactive occlusion control	color	shape	size / height / length	orientation	texture	opacity
Brewer [Bre99]: Color use guidelines				■		■				■				■					
Cleveland & McGill [CM84]: Graphical perception	2D/3D			■					■		■			■	■	■	■	■	
Crawfis & Max [CM93]: Vector field visualization	3D	2	■			■	■	■		■	■	■		■			■		■
de Leeuw & van Wijk [dLvW93]: Local flow probe	3D	-3	■			■			■	■				■	■	■	■		
Healey & Enns [HE99]: Combining textures and colors	2.5D	1	■	■				■	■	■	■			■	■	■	■	■	
Healey et al. [HBE96]: Preattentive processing	2D		■	■				■	■		■			■	■	■	■	■	
Kindlmann & Westin [KW06]: Glyph packing	3D	2	■			■	■	■	■	■	■	■		■	■		■	■	
Kindlmann [Kin04]: Superquadric tensor glyphs	2.5D	1.5	■				■	■	■	■					■		■	■	
Kirby et al. [KML99]: Concepts from painting	2D	1	■			■		■	■	■	■			■	■	■	■	■	■
Laidlaw et al. [LAK*98]: Stochastic glyph placement	2D	2	■			■		■	■	■	■	■		■	■	■	■	■	■
Li et al. [LMvW10]: Symbol size discrimination	2D			■					■						■	■			
Lie et al. [LKH09]: Design aspects of glyph-based 3D visualization	3D	2		■	■		■	■	■	■		■	■	■	■	■	■		■
McGill et al. [MTL78]: Variations of box plots	2D	-3		■	■	■		■	■	■					■	■			
Meyer-Spradow et al. [MSSD*08]: Surface glyphs	2.5D	0	■			■	■	■	■	■	■		■	■	■	■			■
Peng et al. [PWR04]: Clutter reduction using dimension reordering	2D	1		■	■			■	■		■				■	■			
Pickett & Grinstein [PG88]: Stick figures	2D	3		■	■			■	■								■	■	
Piringer et al. [PKH04]: Depth perception in 3D scatterplots	3D								■	■		■	■	■		■			■
Rogowitz et al. [RTB96]: How not to lie with visualization	3D		■	■		■			■	■				■					■
Tominski et al. [TSWS05]: Helix glyphs on geographic maps	2.5D	-2	■		■					■	■	■		■		■			
Treinish [Tre99]: Task-specific visualization design	2.5D	-2	■	■		■			■	■	■			■	■		■	■	
Ward & Guo [WG11]: Shape space projections	2D	3		■	■			■						■	■	■			

Table 2: Categorisation of glyph-based approaches according to design guidelines, visualization space and visual channels. In DG2, the approaches span a spectrum from individual instances of complex glyphs (-3) to dense arrangements of relatively simple shapes (+3).

to encode minimum and maximum value, median, and other quartile information of a data distribution. A negative example in this context would be mapping a data variable to the radius of a circle. The circle's area then increases quadratically with respect to the radius (instead of linearly). Li et al. [LMvW10] study the perception of symbol size, which is assumed to be the second dominant visual channel (after colour [Chr75]). Their experiments suggest that the perception of size can be best represented by a power law transformation. Another negative example would be the usage of a rainbow colour map, which is not perceptually uniform and does not have a perceptual ordering [BT07].

[DG5] Redundant mapping of variables. According to Ward [War08], there are three different mappings:

- a one-to-one mapping assigns each data variable to a different visual channel of the glyph;
- a one-to-many mapping makes use of redundancies by mapping a data variable to multiple glyph channels. Such a mapping can reduce the risk of information loss by encoding important variables multiple times, which is also an important guideline for glyph design [LKH09,ROP11].
- a many-to-one mapping represents multiple data variables by the same kind of visual channel, for example, the height of bars in a histogram or profile glyph. Such a mapping is useful when comparing the different data variables for a data element [War08].

[DG6] Importance-based mapping. According to Ropinski et al. [ROP11], important variables should be enhanced in the visualization, for instance, by using a redundant mapping (compare to the previous guideline). Moreover, the mapping should guide the user's *focus of attention*, e.g., using more prominent visual stimuli such as colour, size or opacity to encode relevance. Ropinski et al. [RSMS*07], for example, use surface glyphs to show data from positron emission tomography (PET). An inverse mapping is used, which maps low PET activity to thick and high PET activity to thin glyphs. Consequently, interesting regions with reduced activity are shown in an enhanced style. Maguire et al propose an algorithmic approach to importance-based mappings [MRSS*12]. Their algorithm builds a taxonomy (a hierarchical classification) from a list of qualitative terms grouped into classification schemes. The higher up some classification scheme is in the taxonomy (determined algorithmically and based on term use for instance), the stronger the visual channel to represent that scheme will be.

3.5.1. Shape Design

One of the most prominent visual channels of a glyph is its shape. Ropinski et al. [ROP11] distinguish between *basic glyph shapes* such as variants of superquadrics [Bar81] (sphere, torus) and *composite shapes* that combine multiple basic shapes. Since basic shapes can be perceived pre-attentively the authors argue that they should be used to convey the most important information. Composite glyphs, on the other hand, are interpreted in the exploration phase and are usually not pre-attentive, i.e., they are analysed sequentially. Chernoff faces [Che73], for instance, represent data variables by different features of a cartoon face (e.g., shape of the face; size and position of eyes, nose, and mouth; curvature of the mouth). The Glyphmaker [RAEM94] provides a user interface that enables non-programmers to map data variables to the different properties of a glyph such as position, colour, shape, overall size and transparency. Kraus and Ertl [KE01] propose a similar tool for scientific data.

[DG7] View point independence: Glyph shapes should be unambiguously perceivable independent of the viewing directions [ROP11]. When using 3D glyph shapes, one has to account for possible distortions introduced when viewing the glyph from a different point of view. Lie et al. [LKH09], therefore, suggest to use 2D billboard glyphs in order to avoid this problem. In certain scenarios, however, it makes sense to use 3D glyphs, for example, when they have a semantic meaning. Such an example would be arrow glyphs that depict a flow field [CM93]. Kindlmann [Kin04] use superquadric glyph shapes that fulfill DG7. For composite shapes, Ropinski et al. [ROP11] distinguish between directional and non-directional glyphs.

[DG8] Simplicity and Symmetry: According to Gestalt laws [War04], simple and symmetric shapes facilitate the perception of visual patterns. Also, simple glyph shapes enhance the detection of minor shape changes as well as outliers [War08]. Peng et al. [PWR04], for instance, automatically reorder the data-to-property mapping for generating more symmetric and simple star glyphs. Lie et al. [LKH09] propose horizontally symmetric glyphs that are based on superellipses, which should facilitate the mental reconstruct of glyph parts that are occluded.

In the following, additional guidelines for shape design are discussed in relation to other visual properties.

3.5.2. Other Visual Properties / Glyph Appearance

Pre-attentive visual stimuli such as position, width, size, orientation, curvature, colour (hue), or intensity are a powerful way to represent data [CM84a, HBE96]. These visual channels are rapidly processed by our low-level visual system and can thus be used for the effective visualization of large data. Special care is required, however, if several such stimuli are combined—the result may not be pre-attentive any more. Healey and Enns [HE99] propose simple texture patterns and colour to visualize multivariate data. Different data variables are encoded in the individual elements of a perceptual texture using equally distinguishable colours and texture dimensions such as element density, regularity and height. Groups of neighboring elements form texture patterns that can be analysed visually.

Ward [War08] identifies different biases that are introduced when mapping a data variable to a glyph property. The first kind of biases are related to human *perception*. Different properties of a glyph can be perceived and related with varying accuracy. Cleveland and McGill [CM84a] identify different visual channels and perform perceptual experiments. The visual channels are ordered based on how accurately they can be perceived: 1) position along a common scale; 2) position along non-aligned scale; 3) length, angle or slope; 4) area; 5) volume or curvature; 6) shading or colour saturation. Moreover, adjacent properties of a glyph are easier to relate and compare than nonadjacent (Ward calls these *proximity*-based biases [War08]). Finally, data variables mapped to semantically or perceptually *grouped* glyph properties (e.g., the ears or eyes in Chernoff faces [Che73]) are easier to distinguish than variables mapped to non-related features.

[DG9] Orthogonality and Normalization: When designing glyphs, it is especially important to consider how different glyph properties interact with each other and thereby possibly distort the interpretation (compared to channel composition [MRSS*12]). A challenge in this context is the *orthogonality* [LKH09] of the different glyph components, meaning that it should be possible to perceive each visual cue independently (or to mentally reconstruct the depicted data variables as suggested by Ropinski et al. [ROP11]). Moreover, one has to account for distortions introduced by the different glyph properties. When using, for example, glyph shape to represent a data variable this affects the area (size) of the glyph as well. Accordingly, such effects should be *normalised* against each other [LKH09]. In the previous example, the overall glyph size could thus be altered in order to compensate for the changes introduced by variations in shape. However, it is not always easy to design a glyph-based visualization such that the different data-to-property mappings are independent and do not influence each other (e.g., the interpretation of shape details is usually influenced by the size of the glyph).

[DG10] Intuitive mapping based on semantics. Semantics of the data should be incorporated in the glyph mapping [War08, LKH09, ROP11, MRSS*12]. Crawfis and Max [CM93], for instance, combine small coloured vector glyphs depicting wind velocity with contour surfaces representing cloudiness. Another example would be to represent temperature with a diverging colour map [Bre99], where white is used to indicated 0°C, blue indicates minus and red plus degrees.

3.5.3. Glyph Placement

The placement of glyphs is a prominent visual stimuli and can be used to convey information about the data. In the context of information visualization, Ward [War02] categorizes placement strategies into *data-* and *structure-driven* placement. The former is directly based on individual variables or spatial dimensions of the data, or on derived information such as principal components. Examples of data-driven strategies are placing the glyphs in a 2D scatterplot or locating them aligned with the underlying data grid (in case of spatial data). Structure-driven placement, on the other hand, is based on the ordering, hierarchical or other relationships of the data variables. According to Ropinski et al. [ROP11] such strategies, however, are not directly applicable to medical data. Therefore, they suggest *feature-driven* placement as an additional category, where glyphs are placed on local data features such as iso-surfaces [RSMS*07, MSSD*08]. We consider it useful to also consider *user-driven* placement, where glyphs are manually placed to investigate the data at a certain location [dLvW93, Tre99].

In the context of data-driven placement [War02], glyphs can be placed according to *derived information* as well. Dimensionality reduction approaches, for instance, aim at reducing the data dimensionality while maintaining the higher-dimensional characteristics. Such placement strategies can facilitate the perception of similar glyph shapes, which should be located close to each other. Principal component analysis [WG11] (PCA) is such an example, which transforms multivariate data into an orthogonal coordinate system that is aligned with the greatest variance in the data. Wong and Bergeron [WB97] apply multi-dimensional scaling (MDS) for mapping higher-dimensional data items into a lower-dimensional space while preserving the dissimilarities between the items. Since MDS also maintains the higher-dimensional structure of the data, it is well suitable for subsequent clustering. With such methods, however, the semantic meaning of the glyph location is usually lost, in contrast to techniques that are based on the raw data [War02].

[DG11] Balanced glyph placement. Glyphs may overlap and form unwanted aggregations in image space, for instance, resulting from a regular data grid. Such aggregations should be avoided, since they may be erroneously identified as features [ROP11, War02]. Laidlaw et al. [LAK*98], for instance, apply random jittering when placing brush strokes to represent DTI data. Kindlmann and Westin [KW06] use a particle system for densely packing superquadric glyphs (Figure 9b). Meyer-Spradow et al. [MSSD*08] evenly distribute surface glyphs by combining a random placement with relaxation criteria.

In the context of glyph placement, the number of depicted data variables must be seen in relation to the available screen resolution (compare to DG2). Large and complex glyphs such as the local probe [dLvW93] can be used when only a few data points need to be visualised (or during individual exploration). If many glyphs should be displayed in a dense manner, however, a more simple glyph may be desirable [PG88, KW06, LKH09].

3.6. Rendering

In the final stage of the visualization pipeline (Figure 8), glyphs are transferred from visualization space to the resulting image, where one has to cope with issues such as visual cluttering, depth perception, and occlusion [LKH09]. In the following, we discuss approaches such as halos, interactive slicing, or brushing.

[DG12] Facilitate depth perception for 3D visualizations. In cases where many glyphs overlap, *halos* can help to enhance the depth perception and to distinguish individual glyphs from each other [LKH09]. Piringer et al. [PKH04] and Interrante et al. [IG98] use halos to emphasize discontinuity in depth and to draw the users attention towards objects. For improving the depth perception for non-overlapping glyphs, a special colour map (called *chroma depth* [Tou97]) can be used to represent depth. Since colour is a dominant visual channel, however, it is questionable whether to use it for depicting depth instead of depicting a data variable.

[DG13] Avoid occlusion by interactive slicing or brushing: Occlusion is a major problem when reading glyphs. Therefore, it can be advantageous to employ interactive slicing or brushing. Using a view dependent slice-based visualization, for example, glyphs that are located in front of a user-controlled plane are not displayed [LKH09]. Using linking and brushing in coordinated multiple views, glyphs can be filtered out based on user-defined criteria [KMDH11].

[DG14] Avoid perspective projections when using glyph size to encode a data variable [ROP11]. In such cases, an orthographic projection is preferable, which supports the comparison of glyph size at different locations.

3.7. Glyph Interaction

Interaction in glyph-based visualizations forms an important aspect in modern visual analytics. Legg et al. [LCP*12] introduce such an example in sport notational analysis, by developing the MatchPad: an interactive visualization software that incorporates a series of intuitive user-interactions and a scale-adaptive layout to support data navigation. One essential requirement in notational analysis in sport is the ability to review key video event footage. Since glyphs have a limited encoding capacity, it would be impractical to map such data (e.g., a video clip, tracking data) entirely to a glyph. Thus, the authors interactively link the playback of videos through glyphs to support rapid information retrieval.

The work of Chung et al. [CLP*13] extends this further by integrating focus+context techniques into glyph-based visual analytics to emphasise the perceptual orderability of attributes on glyphs. They propose a system that incorporates a focus+context glyph-based interface to control and understand high-dimensional sorting of multivariate data. Selected components on the glyph are rendered in focus which adjusts and populates various sorting parameters within a linked *Interactive, Multidimensional Glyph* (IMG) plot. The IMG plot arranges the glyphs along two primary sorting axes. Various interactive tools are described to support user exploration which include: brushing tools for selecting glyphs, pan-and-zoom, and optional display preferences (e.g., connectivity lines) for conveying additional data.

4. Application

Glyph-based visualization is an excellent tool for representing single or multiple data attributes. Whilst generic glyphs are desirable and have been well-studied (e.g., Star glyphs [SFGF72] and Chernoff faces [Che73]), the effectiveness of such designs for conveying information are limited when presented with challenging, complex data forms such as vector and tensor data. In addition to various data type constraints, other factors must be considered. For example, the sampling resolution greatly affects how small or how large the glyph can be in order to avoid visual clutter (compare to DG2). Thus, we find that many glyphs are attribute-dependant and that their specific application context is an integral aspect to the design process. In this section, we report a selection of important papers that focus on novel glyph-based visual techniques that have been explored and utilised in various scientific domains.

4.1. Medical Visualization

The recent survey by Ropinski and Preim [RP08, ROP11] provides an overview of existing glyph-based visualization techniques used in the medical domain and propose guidelines for developing more valuable glyph representations. A glyph taxonomy based on the way information is processed when interpreting glyph visualizations is used to classify such techniques. Within semiotic theory, this consists of a two-phase information process: 1) *pre-attentive* processing, that is mainly stimulated by glyph attributes such as size, colour and shape along with glyph placement, texture mapping and glyph filtering and 2) *attentive stimuli* processes which are based on glyph-interaction paradigms. Examples include a colour legend which users can use to formulate more quantitative glyphs and repositioning glyphs where the glyph properties adapt depending on the location. Based on this classification, the authors describe eight usage guidelines which they evaluate against modern diffusion tensor imaging and cardiac visualization.

Westin et al. [WMM*02] introduce a novel analytical solution to the Stejskal-Tanner diffusion equation system from which a set of derived diffusion tensor metrics describes the geometric properties of a diffusion ellipsoid. Using three tensor eigenvalues, the quantitative shape measures, c_l, c_p, and c_s indicate the linear, planar and spherical properties of a tensor. In addition, the authors present a visualization technique using a composite tensor glyph built from a sphere, disc and rod that are mapped to the three eigenvalues which aims to reduce the ambiguity caused by traditional ellipsoid representation. The composite glyphs are colour-coded according to shape such that blue is mapped to linear case, yellow to planarity and red for spherical case.

Oeltze et. al [OHG*08] incorporate 3D glyphs for visualizing perfusion parameters in conjunction with their ventricular anatomical context. They propose two glyph designs: (a) 3D Bull's Eye Plot (BEP) Segment and (b) 3D Time-Intensity Curve (TIC) Miniatures for depicting four perfusion parameters: *Peak Enhancement (PE)*, *Time To Peak (TTP)*, *Integral* and *Up-slope* which describe the myocardial contractility and viability. The 3D BEP segments are ring-shaped glyphs which extend the previous work [CWD*02] from 2D to 3D space. An improved glyph (TIC miniatures) enables intuitive mapping of all important parameters in cardiac diagnosis as a result of encoding TIC semantic metaphors (glyph shape) that is familiar to domain experts. They apply their technique on three datasets from a clinical study.

The work by Meyer-Spradow et al. [MSSD*08] present an interactive 3D glyph-based approach for the visualization of SPECT-based myocardial perfusion data. They utilise a supertorus prototype glyph which characterises SPECT data based on its colour, opacity, size and roundness. The glyphs are positioned along a 3D surface (i.e., the myocardium) using a random distribution with relaxation for depicting information of the underlying tissue. One motivation of such a placement strategy is to provide a more even-distribution of glyphs. This addresses the problem of unbalanced placement that can occur from regular grid sampling in complex and non-uniform meshes (compare to DG11).

4.2. Event Visualization

Event and activity visualization is a rapidly growing research topic. The work by Botchen et al. [BBS*08] describe the VideoPerpetuoGram (VPG), a dynamic technique for visualizing activity recognition found in video streams. This involves stacking temporally spaced intervals of key video frames and using colour filled glyphs to represent geometric information (e.g., object identifier, position, size), semantic information (e.g., action type and inter-object relation) and statistical information (the certainty and error margins of the analytical results). They demonstrate their technique on surveillance video footage for summarizing the motion of people and actions.

Pearlman and Rheingans [PR07] introduce a glyph-based approach for visualizing computer network security using compound glyphs. The compound glyph representation is a pie chart in which the size and colour of each segment is mapped to the amount of activity and the type of service. One of the motivations of using a simple pie chart design, is its ability to extend to the temporal domain by slicing the glyph as concentric layers for depicting information at different time instances. Each glyph indicates a node on the network in which connectivity lines in the visualization represent the communication between nodes. They successfully demonstrate their method on a simulated network consisting of a small set client users.

The work by Parry et al. [PLC*11] introduce a novel event selection concept for summarising video storyboards. Video storyboard is a form of video visualization, used to summarise the major events in a video using illustrative visualization. There are three main technical challenges in creating a video storyboard, (a) event classification, (b) event selection and (c) event illustration. Among these challenges, (a) is highly application-dependent and requires a significant amount of application- specific semantics to be encoded in this system or manually specified by the users. This paper focuses on challenges (b) and (c) which they demonstrate using a case study on Snooker video visualization. For event illustration, the authors explore a collection of iconic glyphs which convey some metaphors in addition to data values for event labelling. These include ball objects that vary in size, opacity and colour for representing ball trajectory and semantic information (e.g., ball type, event importance), textured circle glyphs and numbered icons for depicting the sequences of shots, and a pie chart icon to represent scoring and video timing information.

A more thorough investigation of incorporating visual semantics into glyph designs is explored by Legg et al. [LCP*12]. They describe the MatchPad: an interactive glyph-based visualization for mapping events and actions in sports notational analysis. Sports event analysis provides an example where a large number of event types need to be depicted in a manner to facilitate rapid information retrieval. A comprehensive review of mapping such data is discussed using different levels of abstractions. These include the evaluation of abstract icons and colour for encoding each event type. Whilst the approach may be suitable for data attributes with a small number of enumerative values, the range of categorical attributes in sports results to many different shapes or colours making it cognitively challenging to learn, remember or guess. Instead, the authors explore the use of metaphoric pictograms which are commonly used in many domain-specific visualization (e.g., electronic circuit diagrams) and visualization for the masses (e.g., road signs). Metaphoric glyphs can come in different forms, ranging from abstract representation to photographic icons (Figure 12), where the use of appropriate visual channels can provide semantic cues that are easy to learn, remember or guess. The MatchPad adopts a scale-adaptive layout to position glyphs along a timeline interactively based on the viewpoint zoom factor. This minimises glyph occlusion which they demonstrate successfully using a case study on Rugby.

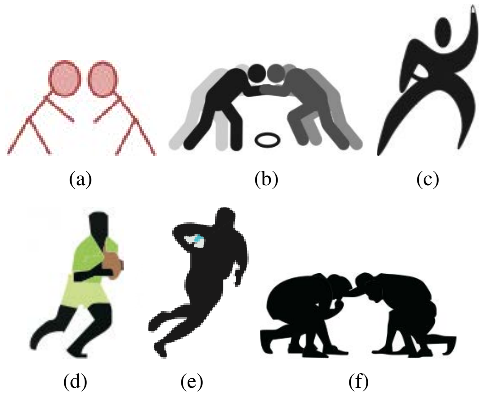


Figure 12: Some designs of metaphoric pictograms for visualizing event data in Rugby by Legg et al. [LCP*12]. In (a), initial stickmen designs were produced to prompt an artist. The artist produced several different designs: (b) a refined stickman design, (c) contemporary design, (d) a posterised colour design and (e) a silhouette design. In (f) the scrum is depicted using the silhouette design (cf. (a) and (b))

4.3. Multi-field Visualization

Due to its multivariate characteristics, geometric shapes are commonly used to represent multiple data attributes. Superquadrics and Angle-Preserving Transformations by Barr [Bar81] presents such an approach by introducing geometric shapes (superquadrics) used for creating and simulating three-dimensional scenes. The author defines a mathematical framework used to explicitly define a family of geometric primitives from which their position, size, and surface curvature can be altered by modifying a family of different parameters. Example glyphs include: a torus, starshape, ellipsoid, hyperboloid, toroid. Furthermore, the author describes angle-preserving shape transformations that can be applied to primitives to create geometric effects such as bending or twisting.

Crawfis and Allison [CA91] introduce a novel approach for visualizing multiple scientific data sets using texture mapping and raster operations. The interactive programming framework enables users to overlay different data sets by defining raster functions/operations. Such a function may include glyph textures for mapping data attributes (e.g., vector data). Using a generated synthetic dataset, they present a method for reducing the visual clutter by mapping colour to a height field and using a bump map to represent the vector and contour plots. The final texture is mapped onto a 3D surface.

Using the set of superquadrics defined by Barr [Bar81], Shaw et. al [SEK*98] describe an interactive glyph-based framework for visualizing multi-dimensional data. As opposed to the analytical focus in the previous work, the authors describe a method for mapping data attributes appropriately to shape properties such that visual cues effectively convey data dimensionality without depreciating the cognition of global data patterns. They map in decreasing order of data importance, values to location, size, colour and shape (of which two dimensions are encoded by shape). Using superellipsoids, they apply their framework to the "thematic" document similarities [SEK*98] and magnetohydrodynamics simulation of the solar wind in the distant heliosphere [E*00], [ES01].

The report by Taylor [Tay02] provides an overview of successful and unsuccessful techniques for visualizing multiple scalar fields on a 2D manifold. The author first hypothesises that the largest number of data sets can be displayed by mapping each field to the following: a unique surface characteristic, applying a different visualization technique to each scalar field or by using textures/glyphs whose features depend on the data sets. Such a framework revealed limitations of up to four scalar fields. This led to the research of two new techniques that prove effective for visualizing multiple scalar fields, (1) *data-driven spots (DDS)* [Bok03] - using different spots of various intensities and heights to visualize each data set, and (2) *oriented slivers* [WEL*00] - using sliver-like texture glyphs of different orientations for visualizing multiple scalar fields in which luminance is mapped to the relative scalar values.

One successful technique is developed by Kirby and Laidlaw [KML99] who stochastically arrange multiple visualization layers to minimize overlap. This paper extends the work by Laidlaw et. al [LAK*98] by applying visualization concepts from oil painting, art and design, to the problems in fluid mechanics. Given a permutation of layers, a user-specified importance value is attached to each visualization of increasing weights in order to provide greater emphasis to higher layers. Visual cues such as colour and opacity indicate regions and layers of importance (e.g., Rate of strain tensor example emphasise the velocity more by using black arrows). This method enables the simultaneous depiction of 6-9 data attributes, in which the authors apply to a simulated 2D flow field past a cylinder at different reynolds number. The example shows the visualization of velocity, vorticity, rate of strain tensor, turbulent charge and turbulent current using a series of visualization techniques such as tensor ellipses, vector arrows and colour mapping.

4.4. Geo-spatial Visualization

We often find that geo-spatial visualization may incorporate inter-disciplinary techniques from other domains, and thus can be classified under more than one category. MacEachren et al. [MBP98] is such an example where the authors present a novel approach to visualize reliability in mortality maps using a bi-variate mapping. Given a base geographical map (United States), the technique involves using colour filled regions to represent the data and texture overlay to represent the reliability.

Healey and Enns introduce a different approach [HE99] using multi-coloured perceptual texture elements known as *pexels* for visualizing multivariate scientific datasets across a height field. The pexels appearance is determined by encoding attribute values into three texture dimensions: height, density and regularity. Pexels incorporate pre-attentive features (e.g., height) to improve the accuracy of visual search-based tasks. To assess its effectiveness, the authors apply their technique on a typhoon data set where wind speed, pressure and precipitation is mapped to the pexel properties.

Pang [Pan01] provides an overview of various geo-spatial uncertainty metrics and identifies two methods for integrating this data into a geo-spatial representation: (a) mapping uncertainty information to graphic attributes (e.g., hue, opacity) or by using (b) animation to convey uncertainty. By treating uncertainty fields as an additional layer of information in cartography, techniques such as uncertainty glyphs can be visualised independently and overlaid on top of an existing geo-spatial visualization.

The work of Sanyal et al. [SZD*10] introduce glyphs, ribbons and spaghetti plots for interactively visualizing ensemble uncertainty in numerical weather models. They demonstrate their work on the 1933 Superstorm simulation, where the visual mappings illustrate the statistical errors (e.g., mean, standard deviation, interquartile range and 95% confidence intervals) in the data.

4.5. Flow Visualization

In the flow visualization community, De Leeuw and Van Wijk [dLvW93] present an interactive probe-glyph for visualizing multiple flow characteristics in a small region. One focus is the visualization of six components: velocity, curvature, shear, acceleration, torsion and convergence. In order to facilitate such a mapping, the authors incorporate a larger glyph design. The core components of the glyph consists of the following: 1) a curved vector arrow where the length and direction represents the velocity and the curvedness is mapped to the curvature, 2) a membrane perpendicular to the

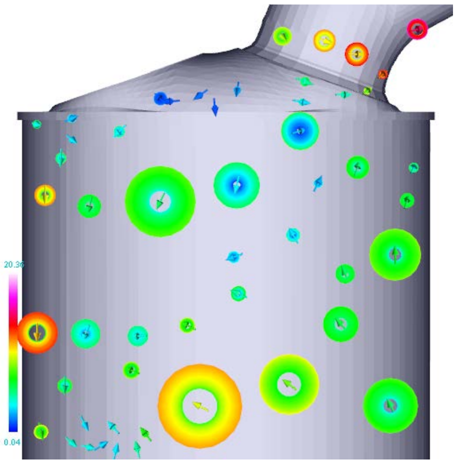


Figure 13: The visualization of vector field clustering of flow around an engine. A combination of $|v|$-range and θ-range glyph is used for depicting the range of vector magnitude and direction in each vector cluster [PGL*12]

flow where its displacement to the centre is mapped to acceleration, 3) candy stripes on the surface of the velocity arrow illustrates the amount of torsion, 4) a ring describes the plane perpendicular to the flow over time (shear-plane), and finally 5) the convergence and divergence of the flow is mapped to a *lens* or osculating paraboloid. Placement of such probes are interactively placed by the users along a streamline to show local features in more detail.

Vector Plots for Irregular Grids Dovey [Dov95] extends Crawfis and Max's method [CM92] from regular to curvilinear and unstructured grids. In order to visualize vector fields on unstructured grids, physical space and parameter space resampling methods are employed. During the physical space resampling, the vector field is linearly interpolated at each sample point, then the physical coordinates of the point are calculated, and lastly related oriented glyphs (plots) are projected from back to front. Although this ensures that sample points are uniformly distributed, physical space resampling is computationally expensive. To address this problem, it may be preferable to resample to parameter space instead. At first, random points are directly generated in parametric space with an area-weighted distribution. Then a relatively accurate and dense resampling can be approximated by mapping the parameterised coordinate to physical coordinate grid points. Vector field visualization on arbitrary 3D surfaces can be efficiently achieved with parameter space resampling.

Martin et al. [MII*08] present a study to validate the effectiveness of traditional 2D hurricane visualizations by observing the users ability to mentally integrate the magnitude and direction of flow in a vector field. In particular, the authors focus on evaluating 2D glyphs (or wind barb) - a technique commonly used for depicting wind magnitude and direction in weather visualizations. For both magnitude and direction, users had to estimate the value at a given point and estimate the average value over a rectangular region. The authors use a real hurricane simulation data set in their study.

Hlawatsch et al. [HLNW11] introduce a glyph for visualizing unsteady flow with static images. The flow-radar (glyph) is constructed by transforming time-dependant vector attributes into polar co-ordinates, whereby vector direction is mapped to angle, and the time to radius. In addition, the velocity magnitude is encoded using colour. The radar glyphs provides a visual summary of the flow over multiple time steps. A method for visualizing flow uncertainty is described using a single arc that represents the angular variation at given seed point. The authors demonstrate their work on two CFD simulation data set.

Peng et al. [PGL*12] describe an automatic vector field clustering algorithm and presents visualization techniques that incorporate statistical-based multivariate glyphs. The authors clustering algorithm is given by: 1) derive a mesh resolution value for each vertex, 2) encode vector and mesh resolution values into R, G, B and α in image space. Clusters naturally form in this space based on pixel intensity. 3) the clusters are merged depending on a similarity value derived using euclidean distance, mesh resolution, average velocity magnitude and velocity direction. A collection of clustering glyph-based visualizations are introduced, such as $|v|$-range glyph or "disc" (Figure 13 for example) that depicts the local minimum and maximum vector. The inner and outer radius of the disc is mapped to the vector magnitudes. The θ-range glyph combines a vector glyph that illustrates the average velocity direction and magnitude, and a semi-transparent cone that shows the variance of vector field direction. Other visualizations include streamlets that are traced from the cluster centre, and colour coding with mean velocity. The authors demonstrate their clustering results on a series of synthetic and real-world CFD meshes.

4.6. Tensor Visualization

The work of Laidlaw et al. [LAK*98] presents two novel methods for visualizing Diffusion Tensor Imaging (DTI). The first method uses normalised ellipsoids, where the principal axes and radii are mapped to the tensor eigen vectors and eigen values respectively. Glyph normalisation reduces the visual clutter and enables full depiction of the data set. The second method incorporates concepts from oil painting to represent seven tensor data attributes as multiple layers of varying brush strokes which is composited into a single visualization. The authors demonstrate their technique on DTIs of healthy and diseased mouse spinal cords.

Building upon previous research by Barr [Bar81] and Westin et al. [WMM*02], Kindlmann [Kin04] introduces a novel approach of visualizing tensor fields using superquadric glyphs. The motivation of superquadric tensor glyphs addresses the problems of asymmetry and ambiguity prone in previous techniques (e.g. cuboids and ellipsoids). An explicit and implicit parameterisation of superquadric primitives is presented, along with geometric anisotropy metrics c_l, c_p, c_s [WMM*02] and user-controlled edge sharpness parameter γ, to create a barycentric triangular domain of shapes that change in shape, flatness and orientation under different parameter values. A subset of the family of superquadrics is chosen and applied towards visualizing a DT-MRI tensor field which is then compared against an equivalent ellipsoid visualization.

Kriz et al. [KYHR05] provides a review of visualization techniques on second-order tensors which include: Lame's stress ellipsoids, Haber glyphs [Hab90], Reynolds tensor glyph [HYW03], and hyper streamtubes [DH93]. Furthermore, the authors introduce a Principal, Normal and Shear (PNS) glyph for visualizing stress tensors and their gradients. The method extends the stress ellipsoids by mapping the shearing stress component to the surface colour of the ellipsoid.

Kindlmann extends his previous work [Kin04] to glyph-packing [KW06], a novel glyph placement strategy. The goal of this work is to improve upon the discrete nature of glyph-based visualization through the use of regular grid sampling, to a more continuous character such as texture-based methods by *packing* the glyphs into the field. A tensor-based potential energy is defined to derive the placement of a system of particles whose finals positions will be used to place glyphs. Hlawitschka et al. [HSH07] presents an alternative glyph packing using Delaunay triangulation which successfully reduces the computation cost.

More recently, Schultz and Kindlmann [SK10] introduce superquadric glyphs that can be used to visualize the general symmetric second order tensors that could be non-positive-definite. The work extends previous glyph-based methods (e.g., [Kin04], [WMM*02]) which concerntrate on tensors with strictly positive eigenvalues such as diffusion tensors, to the general case by mapping the glyph shape to show eigenvalue sign differences. The shape between two eignvectors is convex if the corresponding eigenvalues have the same sign, and concave if they are different.

Chen et al. [CPL*11] present a novel asymmetric tensor field visualization method to provide important insight into fluid flows and solid deformations. Existing techniques for asymmetric tensor fields focus on the analysis, and simply use evenly-spaced hyperstreamlines on surfaces following eigenvectors and dual-eigenvectors in the tensor field. They describe a hybrid visualization technique in which hyperstreamlines and elliptical glyphs are used in real and complex domains, respectively. This enables a more faithful representation of flow behaviours inside complex domains. In addition, tensor magnitude, which is an important quantity in tensor field analysis is mapped to the density of hyperstreamlines and sizes of glyphs. This allows colours to be used to encode other important tensor quantities. To facilitate quick visual exploration of the data from different viewpoints and at different resolutions, the authors employ an efficient image-space approach in which hyperstreamlines and glyphs are generated quickly in the image plane. The combination of these techniques leads to an efficient tensor field visualization system for domain scientists. They demonstrate the effectiveness of their visualization technique through applications of complex simulated engine fluid flow and earthquake deformation data.

4.7. Uncertainty Visualization

A number of approaches have been used to quantify and visualize uncertainty. In particular, glyphs are well suited for illustrating uncertainty, detailed by the early work of Wittenbrink et al. [WPL96] who evaluates the effective use of glyphs for visualizing uncertainty in vector fields simulated from winds and ocean currents. Several uncertainty metrics are depicted simultaneously such as direction, magnitude as well as mean direction and length using a variety of glyph attributes that are commonly mapped (e.g., length, area, colour and/or angles). Lodha et al. [LPSW96] presents a system (UFLOW) for visualizing uncertainties in fluid flow. The system analyses the changes that occur from different integrators and step-sizes used for computing streamlines. The authors visualize the differences between each streamlines using several approaches such as glyphs that encode the uncertainty through their shape, size and colour.

Pang et al. [PWL96] and Verma and Pang [VP04] present comparative visualization tools to analyse differences between two datasets. Streamlines and stream ribbons are generated on two datasets, one being a sub-sampled version of the other. To compare streamlines, the euclidean distance between them is used. Glyphs are added to aid the user in seeing how a pair of streamlines differ. Brown [Bro04] demonstrates the use of vibrations to visualize data uncertainty. Experiments using oscillations in vertex displacement, and changes in luminance and hue are investigated.

MacEachren et al. [MRO*12] is another instance of empirical research that evaluates the effects of visualizing different categories of uncertainty using discrete symbols. Building upon the theoretical framework by Bertin [Ber83] on visual semiotics, they provide insight on the effects of using abstract symbols that vary only a single visual variable (e.g., shape, hue, orientation) in comparison to iconic symbols that are of more pictorial form. Both sets of symbols underwent two distinct experiments which focus on assessing their *intuitiveness* for representing different categories of uncertainty and *effectiveness* for a typical map use task: assessing and comparing the aggregate uncertainty in two map regions.

Ribicic et al. [RWG*12] describe an interactive sketch-based visualization system for investigating simulation models and assess the uncertainty associated with changing different numeric parameters. In particular, the authors demonstrate their approach on flood management simulation as a means of risk assessment. Such an approach provides an intuitive mechanism for transforming sketches into boundary conditions of a simulation and to deliver visual feedback to end-users. A set of glyphs and icons are used to depict various simulation attributes. These include vector glyphs for illustrating the force field on a water flow and ensemble handle glyphs for representing uncertainty values.

5. Summary and Conclusions

In this state of the art report, we have presented a comprehensive survey of the subject of glyph-based visualization. In particular, we have made connection between glyphs and the history of signs and perceptual studies on visual channels and the use of icons. We have brought together a substantial collection of design criteria and guidelines. We have examined a variety of methods and algorithms for visual mapping, computing spatial layout, rendering glyphs and supporting glyph-based interaction. Noticeably, we have gathered an indisputable set of evidence in different applications, suggesting that glyph-based visualization is useful and can bring about cost-effective benefits in many data-intensive tasks.

While this survey has confirmed that glyph-based visualization is an important technique in the field of visualization, we have also observed some doubts in the community about the encoding capability of glyphs primarily due to its size, limited capacity of individual visual channels and cognitive demand for learning and memorization. Although such reservations are very reasonable and cannot be overlooked in any practical applications, they do not undermine the relative merits of glyph-based visualization, which have already been demonstrated in everyday life as well as many applications. These merits include:

- rapid semantic interpretation (e.g., traffic signs [LCP*12]),
- more scalability in dimensions for multivariate data visualization (e.g., [Kin04, SK10]),
- suitable for both dense and sparse layout (e.g., [KW06, LKH09, LHD*04, LCP*12]),
- no significant disadvantage in learning and memorization (e.g., [MdBC00]),
- can be evolved into a standard form (e.g., many schematic diagrams),
- can be evolved into a language (e.g., grapheme-based languages).

This survey has also helped us identify major gaps in the current research on glyph-based visualization. While existing perception studies on visual channels and icons have provided a concrete foundation for glyph-based visualization, most findings are directly applicable only to glyph representations in three or fewer dimensions. We hence would like to encourage more empirical studies on high dimensional glyph representations. As we mentioned in Section 1, glyph-based visualization essentially offers a form of dictionary-based compression. Naturally, this allows us to draw inspiration, theories and techniques from established disciplines, such as data communication and historical linguistics, and research subjects such as information theory, data compression, and lexicography. Perhaps more ambitiously, the field of visualization may channel more energy and innovation into the development of a common framework, which may one day become the basis of a common visualization language.

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