Taxonomy and Usage Guidelines for Glyph-based Medical Visualization

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Abstract

In this paper we investigate glyph-based visualization techniques for the medical domain. We concentrate on both visualization as well as interaction techniques, developed for providing more valuable glyph representations. By taking into account classification concepts established in the area of information visualization, we build up a glyph taxonomy based on the way information is processed when interpreting glyph visualizations. Thus we classify glyph capabilities in those supporting pre-attentive and those supporting *attentive* processing. With respect to the introduced taxonomy, we review glyph-based medical visualizations that have been described in literature. Furthermore, derived from the comparison of these techniques and their suitability for performing a desired exploration task, we propose guidelines for the usage of glyphs in medical visualization.

1 Introduction

Nowadays, medical data sets which are acquired by using medical scanners, contain a multitude of information which needs to be interpreted. In the past, mainly the increasing resolution of the scalar volume data sets posed a challenge for medical visualization. Algorithms had to be developed in order to emphasize structures of interest, which otherwise would have been hidden in the multitude of data. Today, not only the increasing resolution, but also the multiple variables, which can be derived from different modalities or time steps, pose a challenge for providing meaningful visualizations.

At the moment, multi-dimensional data sets accrue mainly in research driven hospitals. However, they are getting more and more attention and are likely to be integrated into standard medical diagnostic processes. One prominent example is the 4D ultrasound acquisition of the human heart, which became a routine diagnosis. With this method it is possible to

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derive multiple variables during one examination, i.e., information regarding the structure of the heart as well as direction and amount of blood flow. Another example for multi-dimensional medical data sets are those acquired by using multimodal medical scanners. When, for instance combining positron emission tomography (PET) with computed tomography (CT) it becomes possible to obtain an integrated visualization of metabolism activity within a high resolution structural context. To address the visualization challenges posed by these high-dimensional medical data sets, glyph-based techniques are a viable option.

In this paper we describe and classify the glyph-based techniques applied in medical visualization. Since glyph techniques are already used in many distinct applications of information visualization, we aim at transferring the established concepts to medical visualization. Ward [War02] states that glyph-based visualization is a powerful method for providing multimodal information by adding iconic glyphs to a scene in order to display various variables. In his work, he classifies different glyph placing strategies and proposes rules for their usage in the context of information visualization. As Bürger and Hauser remark in their state of the art report on multi-variate visualization, glyphs are also a powerful communication item for visualizing multi-variate data in scientific visualization [BH07]. In this paper we solely review glyph-based visualization techniques for medical data sets. In contrast to most applications in information visualization, in glyph-based medical visualization the spatial embedding of the glyphs is of major interest. In almost every case the data is based on a uniform grid, whereas for each grid cell one or more mostly scalar variables are present. The goal of this paper is to classify relevant glyph techniques specifically designed for medical visualization. Thus, we propose a glyph taxonomy for medical visualization and derive usage guidelines for glyph techniques in this area.

Perception-based glyph taxonomy. Glyphs are considered as symbolic or iconic representations of one or more variables of a data set. They are usually geometric objects, whose visual representation can be altered through changing the glyph properties. By using a parameter mapping function, the variables that to be represented can be associated with one or more properties of a glyph, e.g., shape, size or color. The parameter mapping can either be continuous or discrete. When interpreting glyph-based visualizations, the visual representation of individual glyphs as well as the overall structure given by the arrangement of all glyphs can be exploited [War02].

Our proposed glyph taxonomy for medical visualization is based on the theory of perception. Rather than classifying glyph techniques with respect to their technical properties, we address the way they communicate the information to be visualized. According to semiotic theory, stimuli are processed in two phases [RTdOT06]. In the first phase, the pre-attentive phase, the visualized information is perceived parallel as one entity. During this phase, low level information is extracted, which is composed of facts that can be easily perceived. These include the overall structure, difference in shape, and difference in color [War00]. In the second more goal-driven phase of the comprehension process the visualization is analyzed sequentially, i.e., parts of the visualization are identified and observed more detailed, one after another. Due to the conscious nature of this phase, we refer to it as *attentive* phase in the remainder of this paper. According to Treisman, the initial pre-attentive phase is the major step towards improved comprehension [Tre85]. Thus, visualization designers should choose the pre-attentive stimuli wisely in order to communicate the desired information.

In fact, most glyph-based visualizations exploit pre-attentive stimuli, such that the distribution of glyph size, shape and color as well as the glyph aggregation provide important cues in order to aid visual comprehension. However, attentive stimuli are also exploited in current glyph visualizations. They are mainly considered in glyph-based visualizations by exploiting interaction metaphors. Thus, after the low level information is extracted in the pre-attentive phase, the user can interactively explore the glyph visualization. This explorative process is also reflected in Shneidermans *overview, zoom, filter out, details-on-demand* concept, which describes a general explorative task to be initiated through these four steps [Shn96].

Organization. Based on the distinction of pre-attentive and attentive visual information processing, we propose a glyph taxonomy in Section 2, whereas pre-attentive stimuli are discussed in Subsection 2.1 and attentive stimuli are discussed in Subsection 2.2. With respect to the described taxonomy, we will review existing glyph techniques regarding selection of glyph shapes, placement strategies, and interaction concepts developed for certain application areas in Section 3. Based on the findings described in the previous sections, we propose guidelines for the usage of glyph techniques in medical visualization in Section 4, before concluding the paper in Section 5.

2 A Glyph Taxonomy for Medical Visualization

In this Section, we propose a glyph taxonomy for medical visualization, which is based on the two-phase information processing as described in semiotic theory. We distinguish between the consideration of pre-attentive stimuli as described in Subsection 2.1 and attentive stimuli processing through appropriate interaction metaphors as described in Subsection 2.2. To be able to incorporate also glyph-techniques developed in the future, we do not consider entire glyph visualizations, but regard different aspects as glyph shapes, parameter mapping or placement, which are integrated into the taxonomy. While the taxonomy is described in the following subsections, a graphical overview is shown in Figure 1.

2.1 Pre-Attentive Stimuli

In this Subsection, we propose a classification for the most important pre-attentive stimuli exploited by current glyph visualizations. In particular, we distinguish the techniques based on the usage of shapes as well as colors in order to communicate information. Furthermore, we discuss the influence of glyph placement strategies on the perception of glyph aggregations, which can be also perceived pre-attentively.

The pre-attentive stimuli discussed in this Subsection can be exploited only in order to extract low level information, such as the identification of local minima and maxima or the overall structure. To support a quantitative analysis, the attentive processing phase is necessary, which is discussed in Subsection 2.2.

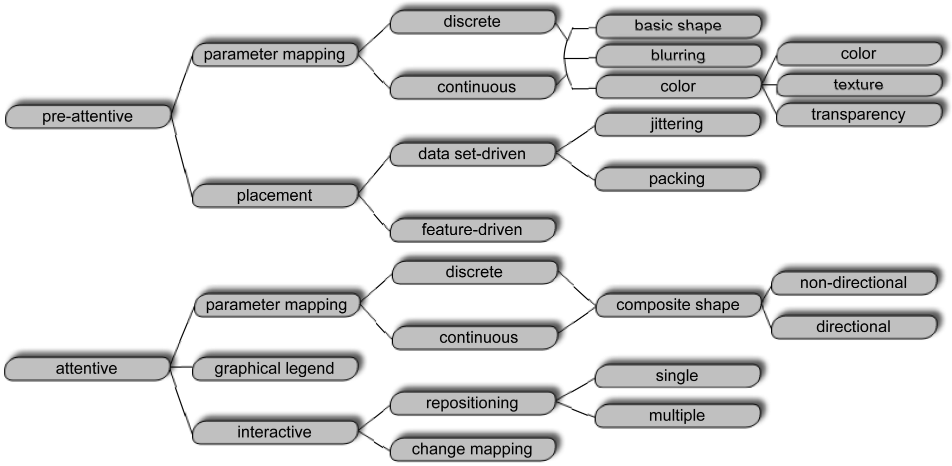


Figure 1: Within our glyph taxonomy we differentiate glyph techniques based on the kind of visual information processing they support. Thus, we classify glyph capabilities into pre-attentive and attentive capabilities.

2.1.1 Glyph Shapes

Modifying the shape of a glyph is the most common way to communicate information using glyph-based visualization techniques. Thus, the shape of a glyph is the main characteristic, which varies tremendously among different glyph techniques. It is important, that the shape of a glyph can be perceived easily and unambiguously [Kin04]. Since the perception of shapes as well as spatial relationships is superior to the perception of colors [CM84], the glyph shapes, and to some extent also glyph placements (see Subsection 2.1.3), are a good way to communicate information.

We distinguish two main groups of glyph shapes: 1. *Basic* glyph shapes are geometric objects, which can be modified by changing their geometric properties,. A basic glyph shape would for instance be a sphere, whereas the property radius can be changed in order to depict information. Other examples are cuboids and ellipsoids as well as superquadric objects. 2. *Composite* glyph shapes, which are composed of the basic glyph shapes. In contrast to the basic glyph shapes, the parameter mapping process for composite glyph shapes requires a more specialized mapping function, i.e., parameters usually cannot be mapped to geometric properties as radius or length. As the name implies, composite glyphs often aggregate different building blocks and are therefore often used to display multi-variate data, whereas each variable can be communicated using another property of the building blocks of the composite glyph shape. Composite glyph shapes are frequently used in information visualization [ERS$^+$99, LRB03]. For the area of scientific visualization, Kraus and Ertl have proposed an intuitive way to model composite glyph shapes out of basic geometric primitives [KE01]. An example glyph generated using their system is shown in Figure 3(a). They also describe how to map parameters to the properties of a customized composite glyph.

Regarding their system as well as other composite glyph shapes, it should be questioned, whether the perception of these glyph shapes can still be considered as pre-attentive. Thus, we assume that mainly basic glyph shapes benefit from the improved perception of shapes and spatial relationships in the pre-attentive phase. However, composite glyph shapes have the capability to communicate more complex information in terms of dimensionality and arbitrary mappings than basic glyph shapes. For instance, the *profile flag* glyph is a combination of basic geometric primitives and a surface used to project more complex information (see Figure 3(b)). Emphasizing their attentive nature, profile flags have been proposed together with probing-like interaction metaphors: One or two glyphs are manually positioned to visualize the data value at a desired position.

We consider directional glyphs as a subset of composite glyphs. When using directional glyphs, the semantic of the visualized data values is taken into account and is expressed by means of the glyph shape, e.g., an arrow is used to communicate a direction of movement. In medical visualization directional glyph shapes may be used to visualize blood flow or tissue movement.

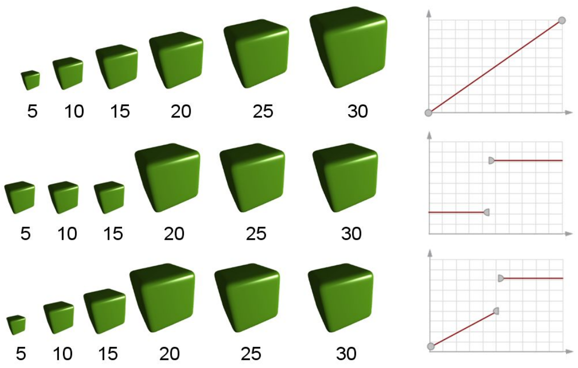
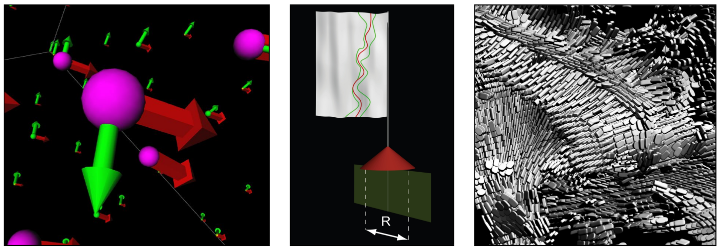


Figure 2: Different mapping functions (right) map a parameter to the size of a superquadric glyph. While visually reconstructing the mapping function based on the shown glyphs is easy for the linear function shown in the top row, it is cognitively more challenging for the discontinuous function in the bottom row.

Continuous and discrete mapping. For both basic and composite glyph shapes, either a continuous or a discrete mapping can be used in order to communicate information based on the glyph's properties. In [RMSS^{+}07], variations of mapping functions are described, such that also a step mapping function can be used in order to allow a better differentiation of the values to be visualized. Such a mapping is shown in Figure 2, whereas glyphs representing different data values are shown next to the respective parameter mapping function. A discrete parameter mapping is found much less frequently in glyph-based medical visualization, than a continuous mapping. Probably, because most variables in medical data sets are scalar. For a superquadric glyph, such a scalar data value can for instance be continuously mapped to its size (see Figure 2). As these continuous mappings often occur in medical visualization, it should be noted that they do not support a quantitative analysis. Since a perspective projection is used in most cases, the size of a glyph cannot be *measured* in image space, without considering the perspective distortion. While when using colors to communicate information, a color scale is sufficient to allow a quantification, this is not sufficient to show the meaning of glyph sizes. Only a tendency can be expressed by using such a scale. Projection comes also into account when considering different glyph shapes in one integrated visualization.



(a) Customizable glyph (b) Profile flag glyph (c) Superquadric glyphs

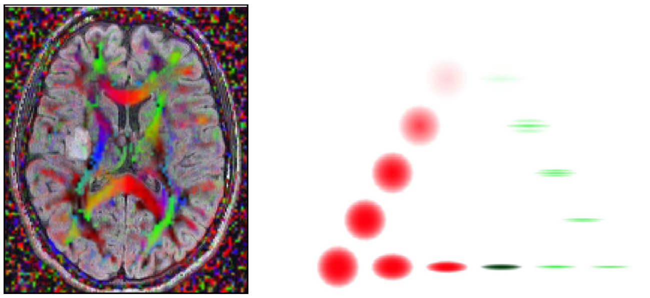
Figure 3: Composite glyphs can be customized in order to depict multiple data values [KE01] (a). More complex information can be visualized by integrating projection surfaces into composite glyphs [MEV^{+}05] (b). Superquadrics can be used as basic glyph shapes, which are unambiguously perceivable [Kin04] (c). (Images courtesy of M. Kraus, M. Mlejnek and G. Kindlmann.)

As mentioned above, it must be also ensured that the shapes are distinguishable independent of the viewing direction. Different approaches have been developed to allow unambiguously perceivable glyphs independent of the viewing direction. Superquadric glyph shapes (see Figure 3(c)) are a group of shapes that satisfies the criterion of unambiguous perception [Kin04].

2.1.2 Glyph Color

Besides a glyph's shape, its color is the property most commonly used to communicate information. In theory, other surface properties could be exploited as well, but obviously changes in color are better perceivable than changes in surface roughness. Similar to the parameter mapping to geometric properties described above, the mapping of values to colors can also be either continuous or discrete. Since a discrete mapping would result in a classification of values, this is again not sufficient for most cases in the area of medical visualization, where the whole range of scalar values should be visualized. Using a continuous mapping is more appropriate, since it allows the user to derive quantities based on the color. However, an absolute quantification is difficult to achieve, because differences in color are harder to perceive than spatial distances [CM84]. Thus color perception can only be used to get an overview during the pre-attentive phase, i.e., local maxima and minima as well as gradients may be identified. In the following attentive phase, color scales can assist the user when interpreting the visualization.

Combining color and transparency to convey directional information. A common extension of color-coding is to employ transparency. Since DTI data are primarily analyzed with respect to the direction of principal diffusion, it is reasonable to use transparency to convey the amount of anisotropy. As an example, the amount of linear anisotropy may be mapped to transparency (maximum linear anisotropy is mapped to zero transparency). With this strategy, directional information is only pronounced if it is reliable. The use of transparency requires some background information, either a constant background color or



(a) The components of the principal eigenvector are mapped to the red-, green- and blue-component of color. Transparency indicates linear anisotropy. In regions with low linear anisotropy, the T2-weighted image is displayed.

(b) Semitransparent colored Gabor patches are used to depict anisotropy from tensor data. If the tensor is isotropic (top corner of the triangle), transparency is 100%. Red indicates that planar anisotropy dominates, whereas green indicates that the tensor exhibits predominantly linear anisotropy. The texture indicates direction in case of strong linear anisotropy.

Figure 4: Usage of color and transparency for DTI visualization [BBH$^+$06]. (Images courtesy of W. Benger.)

anatomic information, such as a T2-weighted image (see Figure 4(a)).

Gabor patches as tensor icons. An interesting approach for tensor visualization was recently introduced by [BBH$^+$06]. It is based on the human shape perception capability which allows to discriminate patterns very well. As a general strategy, they suggest to map tensorial quantities to texture patterns. More specifically, they employ the Gabor filter (see Figure 4(b) and [PZ88]), which conveys directional information well. A Gabor patch is mapped to the plane formed by the principal and median eigenvector (the y-direction of the Gabor patch is aligned with the principal eigenvector). Mapping tensor information to Gabor textures is optionally combined with the previously defined mapping to color and transparency. Thus, directional information is only visualized if it is assessed as reliable based on the relation between the eigenvalues. In summary, anisotropy characteristics are mapped to color, transparency, and texture (see Fig. 4(b)).

2.1.3 Glyph Placement

To achieve a beneficial glyph visualization, not only the shape and the surface properties of the individual glyphs, but also their placement is crucial. Thus, a lot of research has been undertaken in order to generate a meaningful glyph placement. In this Section we classify the existing placement techniques. Ward has already proposed a taxonomy for glyph placement strategies in the context of information visualization [War02]. Some concepts of his taxonomy can be transferred to medical visualization, whereas some concepts should be omitted. For instance, neither a data-driven nor a structure-driven approach for glyph placement should be exploited in medical visualization (data-driven placement is based on the data dimensions and structure-driven placement on the relationship between data points). In contrast, in most application cases in the area of medical visualization, a reproduction strategy as described in [RTdOT06] is exploited. Thus, glyphs are either placed based on the underlying regular grid, or based on the location of features present in the data set. Therefore, we distinguish between *data set-driven* and *feature-driven* placement. Placement on the regular grid is a data set-driven placement strategy, while the isosurface placement described in [RMSS$^+$07] is a feature-driven placement strategy (see Figure 5). Both placement strategies are usually combined with a spatial context and may contain overlapping or non-overlapping glyphs.

When choosing a data set-driven placement, the underlying structure of the regular grid usually has a major influence on the visualization. Thus it can unintentionally emphasize or even feign a non-existent glyph aggregation, which changes depending on the viewing parameters. However, there exists a variety of techniques, which help to avoid this inadvertent effect of the underlying grid structure. Laidlaw et al. [LAK$^+$98] propose a jittered placement in order to reduce the aliasing introduced by the regular grid and thus make the unwanted structures vanish. Bokinsky presents data-driven spots, which are used to display multiple scalar fields [Bok03]. These spots are colored Gaussian splats, which are placed on a jittered grid. A more sophisticated approach has been proposed by Kindlmann and Westin [KW06]. They exploit a particle system in order to generate a packed glyph placement, which combines the continuous character of a texture with the used glyph technique.

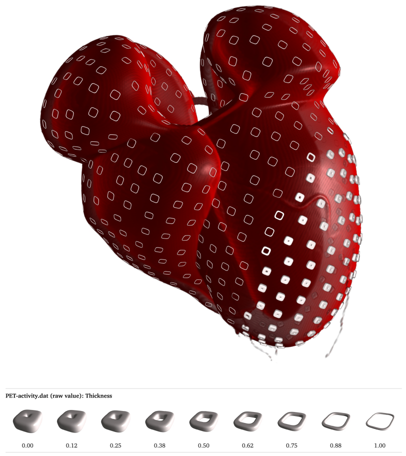


Figure 5: Glyphs depicting PET intensities are positioned on the surface of the myocard extracted from a CT scan. The glyphs are orientated according to its surface normal [RMSS$^+$07].

Glyph filtering. Glyph filtering can also be considered as glyph placement strategy, since less meaningful glyphs can be omitted from display. With glyph filtering, which is often used in information visualization, it is possible to display only glyphs, which satisfy a certain selection criteria. For instance, in the context of DTI visualization, it would be possible to visualize only glyphs exceeding a certain level of fractional anisotropy. Thus, filtering has a major influence on the overall glyph distribution. Modifying this glyph distribution can direct the user's attention, or to emphasize critical data values.

Furthermore, there are techniques, where the initial glyph placement can be interactively modified by moving one or two proxy glyphs through the data set [MEV$^+$05, HSH07]. Since these techniques cannot be considered as pre-attentive processing, we review them more detailed in the next subsection.

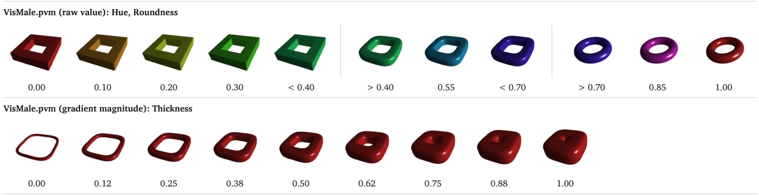


Figure 6: A graphical legend supports the user when interpreting glyph visualizations during a quantitative analysis in the attentive phase of visual information processing [RMSS$^+$07].

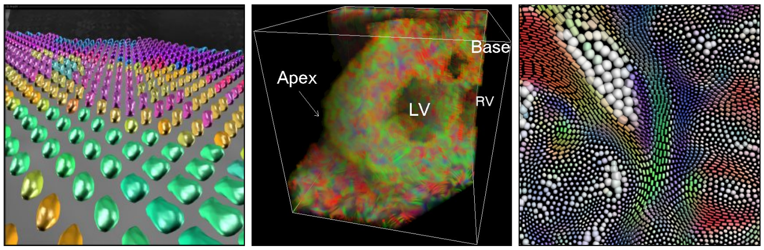
2.2 Attentive Stimuli

In this Subsection we discuss glyph techniques developed for the attentive phase of visual information processing. While the techniques in the previous subsection usually do not support a quantitative analysis, rather a first impression, the techniques described in this subsection allow to get into detail and possibly derive some quantitative results. This reflects quite well the way Shneiderman describes the visual processing: *overview, zoom, filter out, details-on-demand* concept [Shn96]. Whereas the pre-attentive techniques provide an overview, the attentive techniques discussed in this subsection can be used in order to get the details on demand. Thus, we mainly focus on glyph interaction paradigms.

Besides changing the viewing parameters of an interactive 3D glyph visualization, mainly two different interaction paradigms could be identified, which have been developed to explore current glyph visualizations: repositioning of glyphs as well as changing the parameter mapping. These interactive glyphs are also referred to as probing tools [HMK95].

Repositioning glyphs can be compared to as using a color picker tool. The glyph adapts its visual appearance based on the parameter mapping function to the new location it is moved to. Sigfridsson et al. have proposed such positionable glyphs in the context of tensor field visualization, whereas the glyphs can be positioned within a continuous field representation, in order to get quantitative values at the desired position [SEHW02]. A more complex positionable glyph is described in [MEV$^+$05] (see Figure 3(b)). These so-called *profile flags* consist of several basic primitives and allow an efficient exploration of T2 maps of knee cartilage. The glyph has a projection surface for displaying the profile of the map, while the base cone shows which part of the map is considered (see Figure 3(b)). To allow a semi-quantitative analysis, two profile flags can be visualized and repositioned simultaneously such that their visualization is comparable. Thus, it has to be distinguished between single and multiple repositionable glyphs. Further extensions of the profile flag glyph technique are described in [MEV$^+$06].

Changing the parameter mapping is much less frequently considered in literature. Moreover, researchers have focussed on how glyphs can be visualized when a certain parameter mapping is given [KE01, Kin04, DLHL07, RMSS$^+$07]. However, generating such a parameter mapping is crucial and should also be interactive. Especially because different glyph representations may be developed with the goal to emphasize certain features.



(a) Deformed spheres (b) Positionable glyphs (c) Glyph packing

Figure 7: Deformed spheres are used to visualize diffusion directions [DLHL07] (a). Glyphs can be positioned within a continuous tensor field representation [SEHW02] (b). Tensor glyphs are packed in order to achieve a more texture-like effect [KW06] (c). (Images courtesy of L. Linsen, A. Sigfridsson and G. Kindlmann.)

Less interactive but definitely to be considered attentive is the glyph legend proposed in [RMSS$^+$07] (see Figure 6). By using such a legend, the user is able to visually compare the glyphs shown in the current visualization with characteristic glyphs included in the legend. Thus, these legends can be considered as a step towards more quantitative glyph visualizations. However, since glyphs need to be visually matched with the legend glyphs, absolute quantification is still difficult. Additionally, when certain parameters are mapped to a glyph's size, this might be influenced by the perspective distortion, making the visual matching of equally sized glyphs contained in the legend even more difficult.

3 Applications

In this Section, we describe application areas from the medical domain, in which glyph-based visualization techniques are exploited. The goal is not to give an entire overview of described glyph techniques, moreover we pick out diffusion tensor imaging and cardiac visualization as prominent examples. An overview on stress and strain tensor glyphs in non-medical domains can be found in [HYW03].

3.1 Diffusion Tensor Visualization

In the field of scientific visualization diffusion tensor imaging (DTI) is probably the domain where the usage of glyphs has been most intensively investigated. DTI exploits the fact that the diffusion rate of water molecules allows to derive information about the structures of the underlying tissue. In this Subsection, we review existing glyph-based techniques developed for DTI visualization. However, we do not focus on higher order tensor data, which can be also visualized with rather complex glyphs [HSA$^+$07], but focus on second-order tensor fields derived from MR data. It should be mentioned, that glyphs are only suitable for getting a first impression immediately after the acquisition. Glyph visualizations cannot be exploited during an intervention due to many reasons. Besides the fact that brain shift influences the registration of the data sets, glyphs do not explicitly show the underlying fibres which must not be affected during an intervention.

Laidlaw et al. have proposed glyph techniques for the representation of DTI data derived from the mouse spinal cord [LAK$^+$98]. They exploit an array of ellipsoids, where the shape of the ellipsoids present one tensor value, whereas their size is equal due to an introduced normalization. Their second technique uses multiple layers of varying brush strokes, to represent all tensor values. The authors state that the ellipsoids are easier to interpret, while the brush stroke visualization is more quantitative. However, ellipsoids cannot be unambiguously perceived independent of the viewing parameters. Therefore, Kindlmann has proposed superquadric glyph shapes, which fulfill this criterion [Kin04]. The superquadrics are used to convey the principal eigenvectors of a diffusion tensor in order to depict the microstructure of white-matter tissue of the human brain. The distinct glyphs are placed in a regular grid and controlled by a fractional anisotropy threshold in order to minimize visual clutter. Jankun-Kelly and Mehta [JKM06] have adapted the concept and also use superquadric ellipsoid glyphs to visualize traceless tensor data.

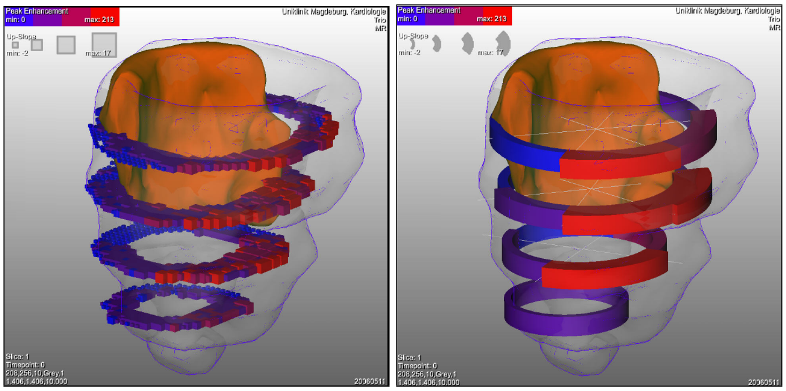
Domin et al. critize, that most glyphs proposed for DTI visualization are not sufficient [DLHL07]. The major drawback is, that the used glyphs do not allow to visualize the possibly arbitrary diffusion directions, since using the tensor minimizes the diffusion directions to only six. They avoid this limitation by using deformed spheres to visualize the diffusion direction (see Figure 7(a)). Therefore, they project each diffusion direction on the surface of the sphere and deform the appropriate surface position according to the diffusion gradient for that direction. Based on the thus given diffusion directions a triangulation is computed, which is further smoothed by applying successive interpolation steps. Thus, the authors state that their technique allows to visualize arbitrary diffusion directions in a natural way. However, it should be investigated how far the deformed sphere geometry can be perceived without introducing a cognitive overload.

Sigfridsson et al. have presented a hybrid approach for visualizing tensor fields [SEHW02]. Their approach combines an overview of the field through adaptive filtering the field containing noise (see Figure 7(b)). While this provides the context, glyphs can be used in the attentive phase in order to get more detailed information. Therefore, the glyphs can be positioned freely.

To avoid the perception of false glyph aggregation, Kindlmann and Westin have proposed their glyph packing algorithm [KW06] (see Figure 7(c)), which was briefly summarized in Subsection 2.1.3. Hlawitschka et al. have also proposed a packing algorithm, which is noniterative and exploits a Delaunay triangulation to perform a proper placement. Thus they are able to achieve fast clustering. However, they describe the packing on a single slice only, which can be moved through the volume. Furthermore, they state that their packing benefits from a simpler parameterization than other techniques.

3.2 Cardiac Visualization

Choi et al. present glyphs specifically used for cardiac visualization [CLYK03]. They propose a technique for accurately measuring diagnostic data, based on a 3D shape reconstruction through fitting a deformable model. The data extractable from the model can be



(a) Grid placement (b) 17-segment model placement

Figure 8: Glyph visualizations developed to support the analysis of cardiac MR data. Perfusion parameters are encoded by cuboid glyphs [POG$^+$07].

visualized by using glyph techniques also in a quantitative manner. With their technique, different variables can be mapped to properties of the glyph allowing a comprehensible visualization of these multi-variate data sets.

Wünsche and Lobb present a glyph-based technique, which allows to visualize deformations of the heart [WLY04]. Based on a generated finite element model, they position ellipsoid glyphs to show the deformation of the myocard. Each glyph is divided into six regions, whereas the region color encodes wether a dilation or a contraction is present.

Ropinski et al. have proposed easily modifiable superquadric glyphs, which they also apply to cardiac visualization [RMSS$^+$07]. With their surface-based placement strategy, they are able to position the glyphs directly on the myocard. Thus, a hybrid visualization of PET/CT data sets becomes possible. The high resolution CT data provides the morphological context, while the low resolution PET data is depicted by using the glyphs (see Figure 5). By choosing appropriate parameter mapping functions, it is possible to guide the user's attention to regions of interest, e.g., areas of the myocard where low PET activity is present.

In [POG$^+$07] glyphs are exploited to visualize cardiac MR data in order to also allow an exploration of the structure and the function of the myocard. Cuboid-shaped glyphs encode the perfusion parameters peak enhancement to color and Up-Slope to slice. The glyphs are placed according to their grid and integrated in a visualization of the left ventricle and scar tissue derived from MR late enhancement data (see Figure 8(a)). Glyphs are aggregated according to a 17-segment model of the American Heart Association (AHA). Thus, each glyph represents a segment in the bull's eye-plot. (see Figure 8(a)).

4 Usage Guidelines

In this Section we propose guidelines for the usage of glyph techniques. Although these guidelines have been developed for applications within the area of medical visualization,

they may also be transferable to a certain extent to other domains.
Besides considering the guidelines proposed below, the glyph visualization designer also has to take into account some constraints posed by the data set to be visualized. An obvious limitation is, for instance, the dimensionality of the visualization or the data set. When dealing with 2D data sets visualized in a 2D visualization setup, 3D glyph shapes are probably not the best choice. Similarly, it is generally accepted when dealing with virtual reality interaction metaphors that the interaction device should optimally have the same degrees of freedom as the model to interact with. Another important though obvious aspect is the number of parameters, which can be mapped to a glyph. When handling vector data, for each component a glyph property should be available. Furthermore, the glyphs should not have more properties than needed for the mapping, since this may misguide the viewer. In addition to these rather obvious considerations, we propose eight usage guidelines for the integration of glyph-based techniques in medical visualization:

1. Parameter mapping functions should visually emphasize important variables.
2. Parameter mapping functions should guide the user's focus of attention.
3. Parameter mapping functions should incorporate semantics of the data.
4. Parameter mapping functions should be *mentally reconstructable* based on the visualization.
5. Glyph placement should avoid unwanted glyph aggregations in image space.
6. Glyph shapes should be unambiguously perceivable.
7. Glyph visualizations should support quantitative analysis in the attentive phase.
8. Hybrid visualization should be exploited to provide the spatial context.

In the following, we briefly describe and motivate these guidelines. As it can be seen, most of these guidelines are focused on choosing an appropriate parameter mapping function. Thus, the specification of the parameter mapping function seems to be crucial to allow more comprehensive glyph visualizations. According to the **first guideline** for the representation of vector data, it should be ensured that the most important variables are more prominent in the final visualization. When, for instance, using a torus-like glyph, the color is better perceivable than the roundness of the glyph. Since the range of values present in a data set have a major impact on the right choice of a mapping function, this range should be considered carefully when specifying the function. Following the **second guideline**, an appropriate parameter mapping can also be used to guide the user's focus of attention. In Figure 5, an inverse parameter mapping is used, i.e., low PET activity is mapped to thick glyphs, while high PET activity is mapped to thin glyphs. By using this inverse mapping, the region of interest, namely the region with reduced PET activity, is visually emphasized. Additionally, according to the **third guideline**, the parameter mapping should be intuitive, i.e., in cases where a glyph property fits semantically to a parameter to be mapped, it should be assigned to this parameter. For instance, in cases where a parameter represents the size of a feature, it should be mapped to the glyph's size. Such an intuitive mapping is presented in [OMP08].

Also colors should be chosen wisely when specifying a color parameter mapping function. In some application cases widely accepted color mappings are present, which should also be considered when exploiting glyph techniques. For instance, PET data sets are often visualized exploiting a heat map, i.e., a yellow-to-red gradient. In cases where no widely accepted color mapping is available, the mapping should be chosen by considering color perception, and eventually the semantics of the variables to be visualized. When taking into account the opponent color model [BM96], two-colored gradients can be generated, whereas the two colors are perceived as lying along the opposite directions of a coordinate axis. According to the opponent color theory, the three color axis are specified by red and green, blue and yellow as well as black and white. However, it should also be considered that the displayed colors influence spatial comprehension. The chromadepth technique [Ste87] supports depth perception based on the fact that the lens of the eye refracts colored light with different wavelengths at different angles. Although this effect can be supported by diffraction grating glasses, watching images without instrumentation can also result in a depth effect.

Furthermore, for all parameter mappings it is important that the mapping supports a *mental interpolation* as stated by the **fourth guideline**, i.e., the user is able to mentally reconstruct the parameter mapping function when viewing distinct glyphs. This can be supported when equal perceptual distances match distances in the range of values, which is true when specifying colors in the CIE color model.

As expressed by the **fifth guideline**, glyph placement is also important for the comprehension of glyph-based visualizations. Since a regular placement on the grid may make non-existent aggregations visible unintendedly [KW06, RMSS+07], this has to be avoided. Therefore, when using a data set-driven placement, at least a jittering has to be applied [LAK+98]. Moreover, when a textual appearance is desired, glyph packing strategies are sufficient in order to avoid misleading aggregations [KW06]. In general, the placement should be chosen in a way that the observer can perceive existent aggregations easily. Thus, also the glyph size and the fact whether glyphs are overlapping or non-overlapping have to be taken into account. Since the glyph size and thus the spacing in between adjacent glyphs is dependent on the resolution of the data set, general guidelines cannot be proposed.

Independently of parameter mapping and placement, the used glyph shapes should also satisfy certain criteria to allow a comprehensible visualization. First of all, glyph shapes should be unambiguously perceivable independent of the viewing direction as stated by the **sixth guideline**. Another important criterion possibly resulting in improved perception is the usage of intuitive glyph shapes. Similar to choosing an intuitive parameter mapping, a glyph shape can be chosen, which expresses the semantics of the variables to be shown. For instance, when considering tissue motion or blood flow direction, directional glyphs as arrows are sufficient.

While the previous guidelines are focussed on the pre-attentive phase, in some cases a quantitative analysis in the attentive phase is desired. For these application cases interaction metaphors, e.g., probing tools [SEHW02], and graphical legends [RMSS+07] should be integrated, as expressed by the **seventh guideline**.

Furthermore, especially when choosing a rather large glyph spacing and thus a lot of context would become visible, the **eighth guideline** should be considered, i.e., the visualization should be enhanced by integrating a spatial context, for instance, by visualizing morphological structures through rendering a CT data set. Since such a hybrid visualization is often described in literature, dealing with glyph-based medical visualization [SEHW02, RMSS$^+$07], it can be assumed as helpful in many cases.

All the above guidelines are motivated by the insights gained during reviewing the current glyph literature. Although these guidelines are also perceptually motivated, we did not conduct an evaluation in order to confirm their advantages. This would be necessary in the future. Probably evaluation approaches could be used from similar studies, as the comparison of 2D vector field visualizations [LKJ$^+$05] or the comparison of isosurfaces, direct volume rendering and glyph visualization for time-varying medical data [TRM$^+$01].

5 Conclusions and Future Work

In this paper we have described a taxonomy for glyph-based medical visualizations. In our taxonomy we classify glyph-based medical visualizations by considering aspects from the area of perception. Thus, we were able to identify glyph techniques supporting pre-attentive and attentive visual processing. With respect to the proposed taxonomy, we have reviewed some existing glyph visualizations from the medical domain as well as other areas.

Based on this review we have proposed eight guidelines that we have formulated with the goal to allow improved glyph-based visualizations in the future. As it can be seen in the guidelines, we have identified the parameter mapping function as crucial for enabling a comprehensible glyph visualization. Therefore, more research should target an intuitive specification of this function. Either by providing interactive systems supporting the specification, or by developing algorithms, which analyze the data to be visualized. Additionally, good viewpoint positions for glyph-based medical visualizations could improve the interpretation.

Although the proposed guidelines have been motivated from the area of perception, a formal evaluation is necessary in order to prove their usefulness.

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