Eurographics Conference on Visualization (EuroVis) (2014)
R. Borgo, R. Maciejewski, and I. Viola (Editors)

STAR – State of The Art Report

A Survey on Interactive Lenses in Visualization

C. Tominski[1], S. Gladisch[1], U. Kister[2], R. Dachselt[2] & H. Schumann[1]
[1]Institute for Computer Science, University of Rostock
[2]Interactive Media Lab, Technische Universität Dresden

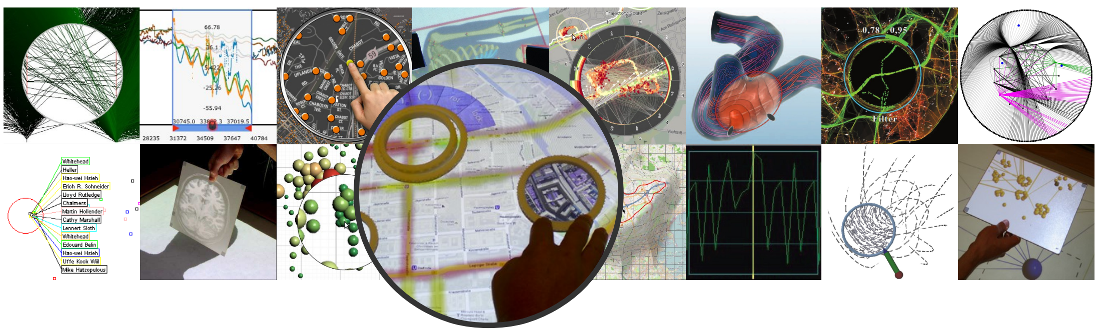


Figure 1: *Examples of interactive lenses in visualization explored with a magnification lens.*

Abstract

Since their introduction in the early nineties, Magic Lenses have attracted much interest. Especially in the realm of visualization, the elegance of using a virtual interactive lens to provide an alternative visual representation of a selected part of the data is highly valued. In this report, we survey the literature on interactive lenses in the context of visualization. Our survey (1) takes a look at how lenses are defined and what properties characterize them, (2) reviews existing lenses for different types of data and tasks, and (3) illustrates the technologies employed to display lenses and to interact with them. Based on our review, we identify challenges and unsolved problems to be addressed in future research.

Categories and Subject Descriptors (according to ACM CCS): H.5.2 [Information Interfaces and Presentation]: User Interfaces—Interaction Styles

1. Introduction

Visualization has become an established means to help people in various fields to gain insight into their data [WGK10]. Yet, as data size is constantly increasing, visualization approaches have to deal with the problem of cluttered and overcrowded visual representations. Moreover, the complexity of the data makes it difficult to encode all facets contained in a dataset into a single visualization image.

Addressing these challenges, visualization researchers utilize concepts such as overview+detail and focus+context [LA94, Hau06, CKB08] as well as multiple coordinated views [Rob07], which facilitate the exploration of large datasets and provide multiple perspectives on complex data. The idea is to enable the user to interactively change the perspective on the data very much in the sense of what Bertin [Ber81] said:

> “A graphic is not ‘drawn’ once and for all; it is ‘constructed’ and reconstructed until it reveals all the relationships constituted by the interplay of the data. The best graphic operations are those carried out by the decision-maker himself.”

Important players in the concert of methods to support interactive multi-faceted data exploration are interactive lenses. The idea behind interactive lenses is to provide on demand an alternative visual representation of the data underlying a local area of the screen. This general concept is

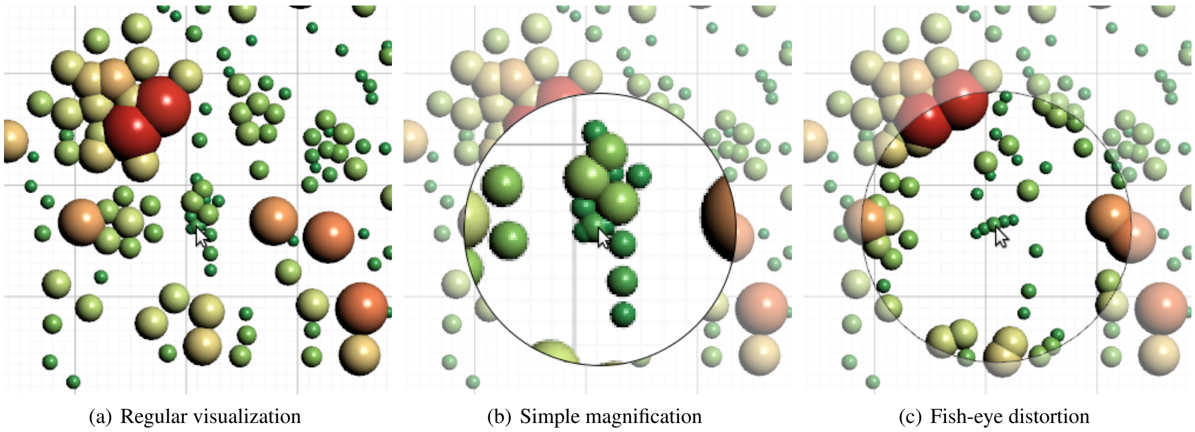


Figure 2: *A data plot with cluttered dots in the center, close to the mouse cursor. A simple magnification lens provides a scaled version of the pixels underlying the lens. In contrast, a fish-eye transformation can be used to distort dot positions to actually untangle the clutter under the lens.*

as simple as it is powerful and versatile. In early works on *magic lenses*, Bier et al. envisioned several possible instantiations of useful lenses, including lenses for magnifying visual items, adjusting graphical properties, querying precise data values, or dynamic filtering [BSP*93, BSF*94, SFB94, FS95, BSP97].

The visualization community with its need for flexible interactive tools to support the exploration of complex data has embraced the idea of interactive lenses. In the last two decades more than 40 lenses have been proposed in the closer context of visualization research, still more in related fields that deal with visual information as well (e.g. human-computer interaction or augmented reality). In this work, we survey the rich body of literature on lenses in visualization.

An Introductory Visualization Example Before going into any details, we shall start with a simple example. Nothing is more simple than a classic magnification lens. Real-world magnification lenses have an ancient history as a tool allowing us to look at details that cannot be seen with the human eye alone. The need to look at details has also motivated early work on overview+detail, focus+context and magic lenses [Fur86, LA94, BSP*93].

An interactive magnification lens is usually defined via a circular shape that is positioned on the screen where a more detailed view is needed. The lens will magnify the content underneath the lens according to a mathematical specification, modifying either the pixels of the display, the geometric model, or even the underlying data.

But what on first sight appears to be rather straightforward turns out to be the result of carefully made design decisions. Consider the visualization depicted in Figure 2(a), which shows dots whose size and color visually encode numerical data values. The dots in the center near the mouse pointer occlude one another making it impossible to identify them individually. A simple magnification of the image's pixels as shown in Figure 2(b) allows us to acquire a bigger picture of the situation, but it does not help to untangle the occlusion. Applying magnification to the geometric model to be rendered will not work either, because it would lead to the same visual output.

Instead a lens is needed that only magnifies distances between the dots, but leaves the dots' sizes untouched. As shown in Figure 2(c), realizing such a lens via a fish-eye transformation helps to clear the view on the dots in a local region. Of course such a temporary distortion is only allowed as long as the dots' positions bear no information that is critical to the task at hand.

Figures 2(b) and 2(c) also illustrate the visual feedback crafted to communicate the fact that a lens is in effect. A circle makes the user aware of the geometric properties of the lens (i.e., shape, position, and size). Further, a virtual veil has been cast on those parts of the visualization that are not affected by the lens, effectively directing the user's attention to the content presented within the lens.

Our introductory example already indicates that interactive lenses can be quite useful and also that there is more to them than simple magnification of image pixels. The next sections will elaborate on the manifold designs, purposes, and implementations of interactive lenses in visualization.

Outline In Section 2, we start with describing how lenses are defined and how they are integrated in the visualization process. Keeping our considerations on an abstract level, we establish a conceptual model that combines the classic visualization pipeline and interactive lenses. Key points are to define where and to what extent a lens takes effect, how the effect is generated, and how the visual feedback is fetched back to the visualization. A description of basic properties of lenses completes the definitional part.

Concrete examples of lens techniques will be given in Section 3. We develop a systematic view on interactive lenses in visualization structured along the two key aspects of visualization: *the data* as the subject of interest and *the task* as the objective of the user. We use a set of data types inspired by Shneiderman's taxonomy [Shn96] to categorize lenses with respect to the data aspect. Yi et al.'s [YKSJ07] categories of user intents for interaction serve to structure the existing lenses according to the task they support. As new lens techniques will be published, they can be easily inserted into this categorization schema.

In Section 4, we consider the technical equipment utilized for interactive lenses. This part is related to the display devices and the interaction modalities that are employed to show lenses (and visualization) and to interactively control them. While many lenses work with a classic desktop setup with regular display and mouse plus keyboard, there are modern technologies (e.g., large high-resolution displays, multi-touch interaction, head-tracking) with new capabilities that can be utilized to make interactive lenses even more useful in visualization.

Moving on from present lens techniques, we will take a look into the future in Section 5. We describe prospects of interactive lenses in visualization and identify corresponding challenges to be addressed in research to come. A brief summary in Section 6 concludes our survey.

2. Definition of Interactive Lenses in Visualization

As illustrated in Figure 3, a lens can be defined as an interactively parameterizable spatial selection according to which a base visualization is altered. Originally, the visible effect of a lens was locally confined to within the lens [BSP*93], in contrast to overview+detail and focus+context techniques that affect the display globally [LA94]. Our survey focuses on lens techniques with a local effect.

Yet, in the context of visualization there are less strict interpretations of what a lens is. A lens might affect the visualization beyond the confines of the spatial selection or even show spatial selection and effect separately. Our survey also includes such techniques as long as they have a lens-like feel or call themselves lenses.

Next in Section 2.1, we will introduce a conceptual model of lenses in visualization. In Section 2.2, we take a look at general properties of lenses.

2.1. Conceptual Model of Lenses in Visualization

To capture the conceptual model behind interactive lenses in visualization, we build upon the well-known visualization pipeline [CMS99]. The visualization pipeline describes how data is transformed from a data source (DS) via data tables (DT) and visual abstractions (VA) to a visualization view (V). We consider lenses in the light of all these different stages of transformations.

Figure 4 shows that a visualization lens can be modeled as an additional lens pipeline that is attached to a standard pipeline. This lens pipeline realizes a *lens function* that generates a *lens effect*. There are two points of information exchange between the standard pipeline and the lens pipeline. The first is a *selection* (denoted σ) that defines what is to be processed by the lens function. The second is a *join* (denoted $\bowtie$) that specifies how the result of the lens function is to be integrated back into the standard pipeline.

The Selection σ The selection describes what is to be affected by the lens. In general, the selection is tightly related to the content underneath the lens. The user controls the selection by adjusting the lens directly on the screen. Figure 4 illustrates that the lens pipeline is executed only for the subset selected from what is originally processed through the standard pipeline. Often it is assumed that the selection is significantly smaller than the original dataset. This allows a lens to perform calculations that would take too long for the entire dataset.

Defined in screen space (V), the lens can be used directly to specify a set of pixels on the display. Yet, in principle the selection can be any information that is available along the visualization pipeline. For example, the fish-eye distortion lens from the introduction (see Figure 2(c)) performs the selection on dot positions. In order to do so, the lens

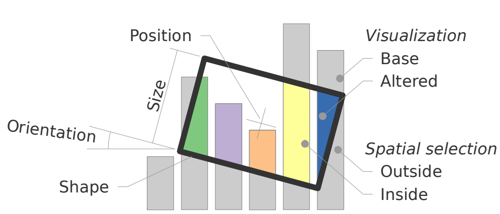


Figure 3: *Schematic depiction of an interactive lens.*

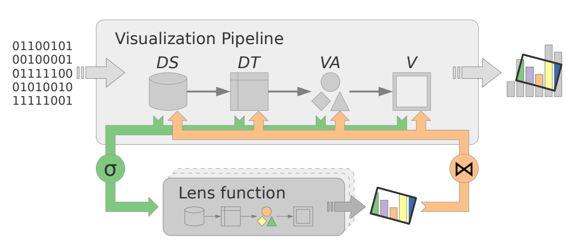
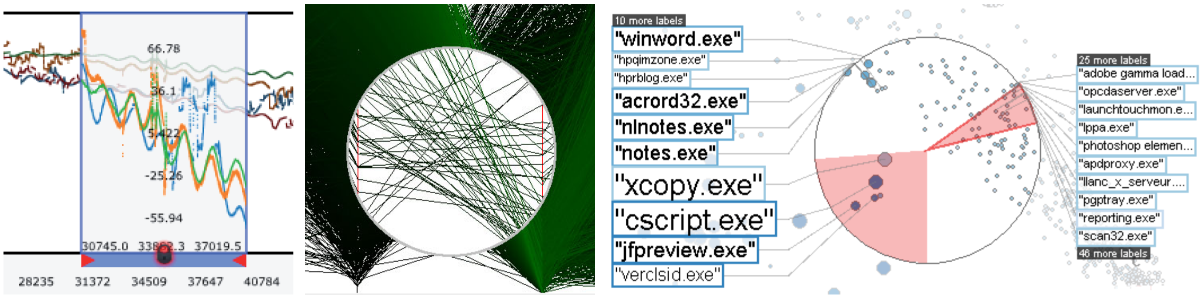


Figure 4: *Conceptual model of lenses in visualization.*



(a) Alteration (b) Suppression (c) Enrichment

Figure 5: *Basic lens functions. (a)* ChronoLenses *[ZCPB11] alter existing content; (b) the* Sampling Lens *[ED06b] suppresses content; (c) the* extended excentric labeling *lens [BRL09] enriches with new content.*

needs to be inversely projected from the screen space (V) to the model space (VA), in which the geometry and graphical properties of the visualization are defined. Further inverse projection to the data space (DT or DS) enables selection at the level of data entities or data values. For example, with the *ChronoLenses* [ZCPB11] from Figure 5(a), the user basically selects an interval on a time scale. The *Local Edge Lens* [TAvHS06] from Figure 7(a) (see two pages ahead) selects a subset of graph edges that pass through the lens and actually do connect to a graph node within the lens.

So, by appropriate inverse projection of the lens, the selection σ can be made at any stage of the visualization pipeline, be it a region of pixels at V, a group of 2D or 3D geometric primitives at VA, a set of data entities at DT, or a range of values at DS. However, what sounds simple in theory is not as straight-forward in real visualization applications. Inverse projection can lead to ambiguities that need to be resolved to properly identify the selected entities. Assigning unique identifiers to data items and maintaining them throughout the visualization process as well as employing the concept of half-spaces can help in this regard [TFS08].

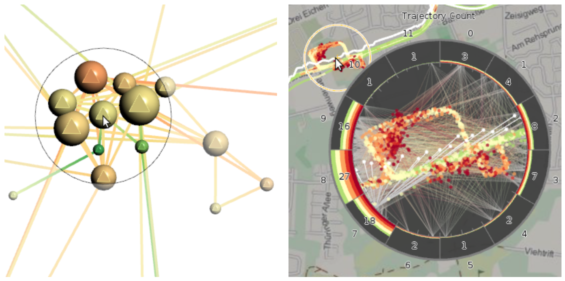
The Lens Function The lens function creates the intended lens effect. Just as any function, so is the lens function characterized by the input it operates on and the output it generates. Clearly, the selection σ is input to the lens function. The lens function further depends on parameters that control the lens effect. Possible parameters are as diverse as there are lens functions. A magnification lens, for example, may expose the magnification factor as a parameter. A filtering lens may be parameterized by thresholds to control the amount of data to be filtered out. Parameters such as these are essential to the effect generated with a lens. Additional parameters may be available to further fine-tune the lens function. For example, the alpha value used for dimming filtered data could be such an additional parameter.

Given selection and parameters, the processing of the lens function typically involves only a subset of the stages of the visualization transformation. For example, when the selection is defined on pixels, the lens function usually manipulates these pixels exclusively at the view stage V. On the other hand, selecting values directly from the data source DS opens up the possibility to process the selected values differently throughout all stages of the pipeline.

The output generated by the lens function will typically be an alternative visual representation. From a conceptual point of view, a lens function can *alter* existing content, *suppress* irrelevant content, or *enrich* with new content, or perform combinations thereof. Figure 5 illustrates the different options. For example, *ChronoLenses* [ZCPB11] transform time series data on-the-fly, that is, they alter existing content. The *Sampling Lens* [ED06b] suppresses data items to de-clutter the visualization underneath the lens. The *extended excentric labeling* [BRL09] is an example for a lens that enriches a visualization, in this case with textual labels.

The Join $\bowtie$ Finally, the result obtained via the lens function has to be joined with the base visualization to create the necessary visual feedback. A primary goal is to realize the join so that it is easy for the user to understand how the view seen through the lens relates to the base visualization. In a narrow sense of a lens, the result generated by the lens function will replace the content in the lens interior as shown for *ChronoLenses* [ZCPB11] and the *SamplingLens* [ED06b] in Figures 5(a) and 5(b). For many other lenses the visual effect manifests exclusively in the lens interior.

When the join is realized at earlier stages of the visualization pipeline, the visual effect is often less confined. For example, the *Layout Lens* [TAS09] adjusts the position of a subset of graph nodes to create a local neighborhood overview as shown in Figure 6(a). Yet, relocating nodes implies that their incident edges take different routes, which in turn introduces some (limited) visual change into the base visualization as well. In a most relaxed sense of a lens, the result of the lens function can even be shown separately. The *time lens* [TSAA12] depicted in Figure 6(b) is an example



(a) Layout Lens (b) Time lens

Figure 6: *Lens effects beyond the confines of the lens interior. (a) Adjusting layout positions of graph nodes via the* layout lens *[TAS09] also affects the edges in the base visualization. (b) The* time lens *[TSAA12] shows the lens' spatial selection and the generated lens result separately.*

where the lens' spatial selection (top-left circle around the mouse cursor) and the generated result (center) are in separate places. Moreover, additional visual feedback can be helpful to support the lens, for example by dimming the base visualization as we have already seen in Figure 2.

An interesting question is how the join is carried out technically. A plausible solution is a three-step procedure. First, one renders the base visualization, optionally sparing the interior of the lens. Second, the result of the lens function is fetched to the lens interior, optionally blending with the base visualization. Third, additional visual feedback is rendered, including the lens geometry and optional user control elements. On modern GPUs, these operations can be accelerated via multiple render buffers, blending masks, and individual shader programs for the different steps.

However, this is not a universal solution. Instead the specific implementation details largely depend on the lens function and the desired effect. For example, the *Layout Lens* [TAS09] from Figure 6(a) is rather easy to implement as it only adjusts node positions at the stage of visual abstractions (*VA*). So the join $\bowtie$ is merely to override the default positions in the standard pipeline with the adjusted positions as computed by the lens. On the other hand, the join can be rather complicated, for example when considering different layers of 3D graphical information that need to be merged in correct depth order.

Discussion The proposed conceptual model identifies the key operations required to design and implement an interactive lens in visualization: a selection σ, a lens function, and a join $\bowtie$. We have seen that all these operations can be carried out at different stages of the visualization pipeline.

There are two noteworthy observation. First, if the selection takes place at the early stages, the lens function has more options for creating a richer lens effect. For example, the *extended excentric labeling* [BRL09] selects data items, which allows the lens function to generate textual labels and place them appropriately. The second observation is that the later the join with the base visualization is carried out, the more confined is typically the visual effect. Joins a the pixel stage as for the *SamplingLens* [ED06b] are usually confined to within the lens, whereas joining at earlier stages as for the *Layout Lens* [TAS09] can have side effects on the base visualization.

Adding even more complexity, our conceptual model in Figure 4 also indicates that it is possible to use multiple lens functions to generate a desired effect [Fox98]. The combination of lenses can be realized by iteratively attaching multiple lens pipelines to a standard pipeline, or by combining lenses recursively. In the latter case, a lens pipeline is attached to another lens pipeline. However, combining lens functions requires proper execution of multiple interdependent selections and elaborate means for blending lens results in a conflict-free way [TFS08]. All this is not easily accomplished and remains a challenge to be addressed in the future as discussed in Section 5.

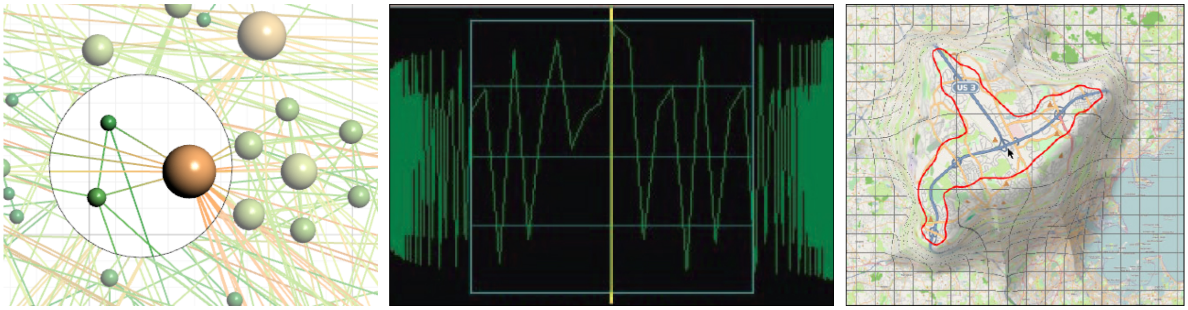
With the conceptual model of lenses in visualization in mind, we can now take a more practical look at the properties of interactive lenses.

2.2. Properties of Interactive Lenses

From a user perspective, the lens geometry is important as it generally determines the spatial selection. In other words, the lens geometry defines where a lens takes effect or at least which data entities are affected. The key properties to look at are: the lens shape, the position and size of a lens, as well as the orientation of a lens.

Shape The most prominent property of a lens is its shape. In theory, there are no restrictions regarding the shape of a lens, but it is usually chosen to meet the requirements of the application and to go hand in hand with the lens function. Following the classic prototype of real-world lenses, many virtual lenses are of circular shape. An example is the *Local Edge Lens* [TAvHS06] as shown in Figure 7(a). Yet, in a world of rectangular windows on computer screens, it is not surprising to find lenses that are of rectangular shape, such as the *SignalLens* [Kin10] in Figure 7(b).

An interesting alternative to lenses with a pre-defined shape are lenses that are capable of adapting their shape automatically according to the characteristics of the data. Such self-adapting lenses are particularly useful in cases where the lens effect needs to be confined to geometrically complicated features in the visualization. Examples are the *smart lenses* [TFS08], which adjust themselves to shapes of geographic regions, or the *JellyLens* [PPCP12], which morphs around arbitrary geometric features in the data. A JellyLens is depicted in Figure 7(c).



(a) Circular shape (b) Rectangular shape (c) Content-adaptive shape

Figure 7: *Lenses with different shapes. (a) Circular* Local Edge Lens *[TAvHS06]; (b) Rectangular* SignalLens *[Kin10]; (c) Content-adaptive* JellyLens *[PPCP12].*

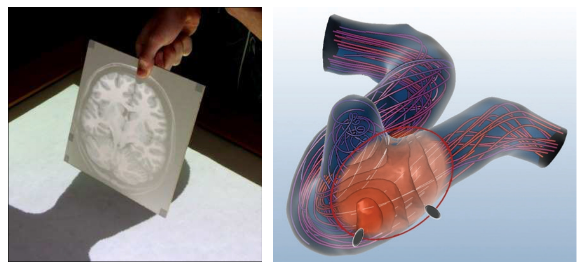
While two-dimensional shapes are prevalent, there are also lenses with 3D shapes. They are typically used for the visualization of 3D data or 3D graphics in general. Examples are lenses for flow visualization [FG98], for magnification of volume data [LHJ01], lenses for 3D scenes [CCF97, RH04], or bendable virtual lenses [LGB07].

Position and Size In order to be flexible in terms of where the visualization is to be altered, interactive lenses are parameterizable. Parameters provided by virtually all lenses are position and size. The position of the lens can be adjusted to focus on different parts of the data, whereas scaling a lens up and down controls the extent of the lens effect. Taken together, moving and scaling enables users to properly attune a lens to the data features they are interested in.

Moreover, parameterizing the size of a lens is useful for keeping costs at a level that warrants interactivity and comprehensibility at all times. This concerns computational costs, i.e., the resources spent for computing the lens effect, but also cognitive costs, i.e., the effort required to make sense of the lens effect.

A large part of the interactivity attributed to lens techniques pertains to direct manipulation [Shn83] of the lens, which effectively means adjusting its position and size. Complementary to interactive adjustment are methods to set position and size of a lens automatically. For example, to guide users to interesting events in the data, one can automatically position a *Table Lens* [RC94] according to those data tuples for which events have been detected [Tom11]. An example of a lens that automatically adjusts its size to cope with expected costs is the *extended excentric labeling* lens [BRL09]. This lens reduces its size in areas where too many items to be labeled are present.

Orientation A less apparent parameter of a lens is its orientation. In classic 2D visualization applications, the orientation of a lens is less important and therefore often neglected. In fact, for circular lenses, orientation does not even make sense. Yet, orientation can be useful for fine-tuning the lens or is even needed to define the spatial selection at all. As illustrated in Figure 8(a), the *PaperLens* [SSD09], for instance, relies on 3D orientation to define a slice through a virtual volume in the space above a tabletop display. For another example consider the ellipsoid *FlowLens* [GNBP11] in Figure 8(b) and how it is oriented to better match with the underlying visualization.



(a) *PaperLens* [SSD09] (b) *FlowLens* [GNBP11]

Figure 8: *Examples of differently oriented lenses.*

Orientation becomes more important in settings where multiple users look at a common display from different angles, as it is the case for collaborative work at a tabletop display [VTS*09]. An example is a user who is handing over a lens to a co-worker at the opposite side of the table, which for certain involves re-orienting the lens.

In summary, we see that lenses exhibit several key geometric properties that can be interactively or automatically adjusted. In addition to what we described here, there can be further parameters, for example, a depth range for 3D lenses or a drop-off interval for fuzzy lenses.

In the next section, we broaden our view of lenses from the conceptual model and geometric properties to actual lens techniques for different types of data and different tasks.

3. The Data, The Tasks, and Their Lenses

By considering data and tasks, we shift our focus to aspects that are more of interest to users of visualization tools. Such users may ask: I'm working with this and that type of data, is there a lens for the task I have to accomplish with my data? The following paragraphs aim to provide an answer to this question. As a first part of the answer, we will look at lenses for different types of data. For the second part of the answer, we will study lenses for different tasks.

3.1. Lenses for Specific Data

There are general purpose lenses and there are lenses that are specifically designed for a particular type of data. Lenses that operate on pixels or geometric primitives are usually oblivious to the specific data type of the underlying visualization. For example, magnification lenses (e.g., [Kea98, CM01, CLP04, FS05, PPCP12]) are techniques that are universally applicable across many, if not all types of data.

In this section, we focus on lenses that specifically address the characteristics of the visualized data. Our survey of data-specific lenses is inspired by Shneiderman's taxonomy [Shn96]. Yet, we use a slightly different set of data types, which we think is more descriptive:

- Temporal data
- Geo-spatial data
- Volume data
- Flow data
- Multidimensional and multivariate data
- Graph data
- Text and document data

We illustrate the diversity of existing lens techniques by describing one exemplary lens for each of these data types very briefly. A more comprehensive overview of existing lenses for different types of data is provided in Table 1.

Temporal data Data that have references to time are commonplace. Time series allow us to understand the development of past events and estimate the future outcome of ongoing phenomena. Analyzing time series often involves normalization, elimination of seasonal effects, and other temporal transformations. *ChronoLenses* [ZCPB11] enable users to carry out such operations for selected time intervals (σ). The transformed part of the time series is overlaid ($\bowtie$) with the original version to maintain the context and facilitate comparison.

Geo-spatial data Data about the world around us often hold references to the geo-spatial domain, describing where certain features could be observed. Maps are frequently used in visualization applications to serve as a basis with respect to which the actual data are depicted. As maps are omnipresent in our everyday lives, it is not surprising to find a lens developed for a routine problem: *Detail Lenses* [KCJ*10] aim to make the visual representation of driving directions on maps easier to follow. To this end, relevant points of interest (POI) are defined (σ) along a route. For each POI, a lens with a detailed map of the POI is arranged around a global overview map ($\bowtie$).

Volume data Volume data are scalar data values on a three dimensional grid. Hence, lenses for volume visualization face the typical challenges related to spatial selection and occlusion in densely packed 3D visual representations. The *Magic Volume Lens* [WZMK05] addresses these challenges. In fact, the authors propose different lenses to magnify volumetric features, while compressing the context without clipping it entirely. The selection (σ) can be made interactively or can be adapted to data features automatically. The lens effect is directly embedded ($\bowtie$) into the direct volume rendering through a multi-pass rendering strategy.

Flow data 2D or 3D vectors are the basic components of flow data. In addition to the raw vectors, derived scalar attributes, higher-level features (e.g., vortices), and flow topology are relevant aspects of the data. Fuhrmann and Gröller [FG98] are among the first to propose lens techniques specifically for flow data. They use a planar 3D lens polygon or a volumetric 3D lens box to implicitly or explicitly define a 3D spatial selection (σ) in the flow for which more details are to be shown. The low-resolution base visualization is replaced ($\bowtie$) by filling the lens interior with more and thinner streamlines that also have an increased number of control points.

Multidimensional and multivariate data General multidimensional, multivariate data typically span a frame of reference across multiple abstract dimensions. Along these dimensions multiple quantitative or qualitative variables are measured. Dealing with data size is usually challenging. The *Sampling Lens* [EBD05, ED06b, ED06a] addresses the problem of clutter in scatter plots and parallel coordinates. Through sampling, the lens function generates a more sparsely populated alternative view on the data. The selection (σ) made with the lens is inversely projected into the data space in order to estimate a suitable sampling rate for the alternative visual representation to be shown inside the lens. The clutter-reduced visual representation of the sampled data is rendered and clipped ($\bowtie$) at the lens boundaries.

Graph data A graph is a universal model for describing relations among entities. Although sophisticated graph layout algorithms exist, visual representations of graphs might still suffer from ambiguities. The *EdgeLens* [WCG03] (and later the *PushLens* [SNDC10]) address this problem by reducing the number of edges being visible inside the lens. The selection (σ) singles out edges that intersect with the lens geometry, but whose source and target vertices are not inside the lens. Then the lens interior is cleared of the selected edges by 'bending' ($\bowtie$) them around the lens.

Text and document data Text and document collections are rich sources of information. Analysis of text typically focuses on important topics or themes and querying relevant keywords. A particularly interesting application of a lens for exploring text databases is the approach by Chang and Collins [CC13]. What makes their lens special is the fact that they combine spatial and abstract semantics in a single view. The lens selection (σ) operates on a 3D model of a car capturing the spatial semantics. Associated with the spatial selection are keywords, which capture the abstract semantics. Keywords corresponding to the selection are visualized as heatmap charts around the lens and an additional panel provides access to the underling text documents ($\bowtie$).

In the previous paragraphs, we have briefly reviewed examples of lenses for different types of data. In the next section, we will focus on lenses for specific tasks.

3.2. Lenses for Specific Tasks

Lenses are designed as interactive tools. So it makes sense to review lens techniques in terms of the interaction tasks they do support specifically. In order to structure such a review, we draw inspiration from Yi et al. [YKSJ07], who describe seven key categories of user intents for interaction:

- Select
- Explore
- Reconfigure
- Encode
- Abstract/Elaborate
- Filter
- Connect

Each intent captures why a user wants to or needs to interact in the course of carrying out exploratory or analytic tasks. Similar to what we have done for different types of data, we will now very briefly describe exemplary lenses for each category to illustrate their utility for the different interaction intents. Table 1 lists further references.

Select – Mark something as interesting A typical problem in dense visual representations is to pinpoint data items of interest. An example of lens techniques that supports this task are the high-precision magnification lenses [ACP10]. These lenses make picking data items easier by actually enlarging not only the visual space in which visual feedback is shown, but also the motor space in which users interact.

Explore – Show me something else Exploration relates to undirected search, the user is interested in seeking out something new. The *tangible views* for information visualization [STSD10] demonstrate a variety of exploratory lens methods. An example is the exploration of space-time cubes via sliding a tangible view through a virtual space-time continuum above a tabletop display. This enable the user to focus on different points in time and different places in space.

Reconfigure – Show me a different arrangement The spatial arrangement of data items on the screen is key to comprehending the visualized information. Looking at different arrangements helps to gain a better understanding of the data. A lens that temporarily rearranges the visual representation is the *Layout Lens* [TAS09]. By relocating graph vertices to the lens interior, local neighborhood overviews are created to support connectivity-related analysis tasks.

Encode – Show me a different representation The visual mapping decides about the expressiveness of a data visualization. Yet through a global encoding for the data as a whole, details in local regions may be difficult to spot. The *Color Lens* [EDF11] adapts the color coding according to the local conditions underneath the lens. The effect can be shown in multiple local lenses and alternatively can replace the global encoding temporarily.

Abstract/Elaborate – Show me more or less detail This rather general task is supported in many different ways. Various general purpose lenses have been proposed that show more detail through magnification. The lens technique by van Ham and van Wijk [vHvW04] provides access to more details via automatic expansion of clusters in a hierarchical graph. Vertices that are no longer in the focus of the lens are automatically collapsed to higher levels of abstraction.

Filter – Show me something conditionally Filtering according to specific criteria, while still maintaining a global overview is an important task when exploring data. In some cases, filtering even acts as an enabling technique for the visualization. For example, the filtering capabilities of *TrajectoryLenses* [KTW*13] enable the visual exploration of massive movement data. Filtering can be done according to origins and destinations of movements, regions passed by movements, and time intervals spanned by movements.

Connect – Show me related items Once the user has focused attention on data items of interest, the exploration usually continues with related or similar data. The Bring & Go approach [MCH*09] is a lens-like technique that supports navigation to related items in graphs. All vertices that are related (i.e., connected) to a focus area are brought close to the focus. Clicking triggers an animated trip to a selected vertex.

Already the limited number of approaches briefly mentioned in this section indicate that lenses are broadly applied in visualization for different data and different tasks. As it is impossible to describe the existing lens techniques in greater detail here, the reader is referred to the original publications collected and categorized according to data type and task in Table 1. Still more references and additional brief captions are collected in the appendix.

This section presented lenses in terms of their semantics. The next section will focus on how users actually work with lenses using different display settings and interaction modalities.

	Data							Tasks						
Techniques	Temporal	Geo-spatial	Flow	Volume	Multivariate	Graph	Document	Select	Explore	Reconfigure	Encode	Abstract & Elaborate	Filter	Connect
[SB92, SB94] Fisheye Views		●				●						●		
[RM93] Document Lens							●					●		
[CMS94] MagicSphere				●				●			●	●	●	
[RC94] Table Lens					●							●		
[VCWP96] 3D Magic Lenses				●								●	●	
* [FG98] Lenses for Flow Visualization			●								●	●		
[FP99] Excentric Labeling					●									●
[SHER99] Interactive 3D Lens			●	●	●		●				●	●	●	
[LHJ01] Volume Magnification Lens				●								●		
[SFR01] Time Lens	●								●					
[BCPS02] Fuzzy Lens, Base-Pair Lens, Ring Lens						●				●	●	●		
[MTHG03] 3D Flow Lens			●								●	●		
* [WCG03] EdgeLens						●				●				
* [vHvW04] Graph Abstraction Lens						●						●		
[RHS05] Magic Lenses in Geo-Environments		●									●		●	
* [EBD05, ED06b, ED06a] Sampling Lens					●								●	
[RLE05] Temporal Magic Lens	●								●					
* [WZMK05] The Magic Volume Lens				●								●		
[TAvHS06] Local Edge Lens						●							●	
[TGBD08] 3D Generalization Lenses		●										●		
* [TAS09] Layout Lens						●				●				
[BRL09] Enhanced Excentric Labeling					●									●
* [MCH*09] Bring &Go						●				●				●
* [ACP10] High-Precision Magnification Lenses	●	●	●	●	●	●	●	●				●		
[JDK10] Network Lens						●					●			
* [KCJ*10] Detail Lenses for Routes		●										●		●
[Kin10] SignalLens	●											●		
* [SNDC10] PushLens						●				●				
* [STSD10] Tangible Views		●			●	●		●	●	●	●	●	●	●
* [EDF11] Color Lens	●	●	●	●	●	●					●			
[GNBP11] FlowLens			●						●		●		●	
[HLTE11] SemLens					●						●		●	
[HTE11] MoleView		●			●	●				●				
[LWG11] Facet Lens							●				●		●	
[PBKE11] EdgeAnalyser					●	●					●	●		
[ZCB11] MagicAnalytics Lens	●													●
* [ZCPB11] ChronoLenses	●												●	●
[TSAA12] Time Lens		●							●		●			●
[PPCP12] JellyLens		●										●		
* [KTW*13] TrajectoryLenses		●											●	
[PPCP13] Gimlenses				●								●	●	
[UvK13] Magic Lenses for Hypergraphs						●							●	
* [CC13] Lens for Querying Documents							●						●	●

Table 1: *Lens techniques in the context of visualization categorized according to data types and tasks. Entries are sorted in chronological order. Techniques for which a brief description is available in Section 3 are marked with *.*

(a) Multi-touch interaction (b) Tangible interaction (c) Spatial interaction

Figure 9: *Examples of different interaction modalities for lenses. (a) Bimanual touch interaction in* FingerGlass *[KAP11]; (b) graspable interaction through* TangibleRings *[EWCP13]; (c) interaction above the tabletop with* Tangible Views *[STSD10].*

4. Interaction and Display

Interactive lenses in visualization take advantage of various interaction modalities and show their visual feedback on different kinds of displays. Interactive operations that have to be considered include creation and deletion of lenses, manipulations of the lens geometry (recall the properties discussed in Section 2.2), as well as more complex operations, such as parameterizing the lens function or combining multiple lenses. However, these interactive operations are rarely discussed in detail, because usually it is the lens function that is in the focus.

The goal of this part of our survey is to illustrate the wide variety of interactive visual environments that serve as a technical basis for interactive lens techniques. Illustrating examples of different display settings and interaction modalities are given in Figure 9. In the next sections, we will discuss interaction with lenses in the context of a variety of styles and modalities. These include:

- Mouse and keyboard interaction
- Touch and multi-touch interaction
- Tangible interaction
- Tangible views and spatial interaction
- Gaze-based interaction and head tracking

We start with looking at traditional visualization environments, which typically consist of a single display and mouse and keyboard input devices. However, such environments quickly reach their limits in the face of complex analysis tasks performed on big data. The single display limits the amount of information that can be shown at a time and mouse and keyboard interaction is limited to a single user.

New visualization environments address these limitations in different ways. Interactive tabletop displays [IIH*13] and multi-display environments [EBZ*12] provide more display space for the visualization and enable multiple users to work collaboratively. Specifically because of their local effect, lenses in combination with large interactive surfaces or displays can become powerful tools for collaboration. A good example is the work by Waldner et al. [WKS07]. In their setting several users can gain an alternative view on the data through optical lenses by utilizing polarized light on large-scale projector-based displays. As more than one person can work with the visual representation of the data, joint data exploration and analysis becomes less tedious. Yet, there are also additional challenges that need to be addressed. On tabletops, the orientation problem arises when multiple users stand on different sides of the table looking at lenses and visualizations. On large high-resolution displays, covering large distances causes considerable difficulties. Context-dependent interaction techniques are required to enable multiple users to make the best of interactive lenses in such new visualization environments.

4.1. Mouse and Keyboard Interaction

Mouse and keyboard interaction has been the most common interaction modality of the last decades. Therefore, it is no surprise that it is also the most prominent in the reviewed research on lenses. The typical environment of mouse and keyboard interaction is a one-to-few display setup for a single user. The precision of the cursor movement is the major advantage of mouse input. Additional possibilities of the mouse are given through mouse buttons and the mouse wheel, which can be used for discrete or continuous input, respectively. Keyboard input, on the other hand, is suitable for mode switches or step-wise navigation.

The direct manipulation of the mouse is especially useful when specifying the region of interest and hence repositioning of the lens. This technique is used in many of the examined research works, for instance in [BCPS02, ED06a, PPCP12, TAvHS06, WCG03]. As the lens position is coupled with the mouse cursor, fast repositioning becomes possible. However, when a magnification lens is used, this fast positioning at context scale can hinder target acquisition in the focus area and make pixel-precise positioning impossible [ACP10].

Appert et al. [ACP10] introduce different interaction techniques to improve on the target selection when using magnification lenses. First, they present mode switching between focus and context speed by using a keyboard key. Second, they provide a continuous mapping between precision of lens movement depending on cursor speed. The third interaction technique introduces a ring as the lens border where the lens' inner region is navigated at focus scale while the outer region is navigated at context scale. In the experiments, all techniques performed better than regular lens positioning and the ring technique performed best in experiments for small targets and high magnification factors without needing the additional keyboard mode switch.

To incorporate the adjustment of parameters other than position, mouse buttons are used to toggle a specific parameter or state [BRL09, HTE11]. Additionally, the mouse wheel can be helpful when changing continuous values, such as attribute ranges [HTE11]. However, as more and more parameters have to be adjusted for complex lens functions in visualization, graphical user interfaces are necessary. Possible controls and widgets include toolbars, combo boxes, or sliders. The mouse is then used to adjust these parameters in either global or context menus. Some examples can be found in Jusufi et al.'s work where a dialog box is used to create and edit the *Network Lens* [JDK10]. The *Sampling Lens* [EBD05] is another example, as a slider is used for lens diameter adjustment.

In three-dimensional visualizations, adjusting the lens geometry in relation to the data becomes difficult. For CAD models, Pindat et al. [PPCP13] use mouse interaction for positioning the lens with the help of automatic orientation constraints and virtually drill into the visualization using the mouse wheel. For their lenses for 3D flow visualization, Fuhrmann and Gröller [FG98] suggest a 3D mouse or tracked pen to reconfigure the six degrees of freedom. The *Document Lens* [RM93] is controlled with mouse interaction for the x-y-plane positioning and with keyboard keys for movement within the z-plane.

4.2. Touch and Multi-Touch Interaction

In the past decade, touch devices have become increasingly commonplace. Especially noticeable is the upsurge of touch-enabled personal devices, such as smartphones and tablets, but also interactive displays for desk work, such as touch-screen monitors, became accessible. Additionally, touch-enabled devices can be enhanced with digital-pen recognition. Such devices allow for direct interaction in context and natural interaction with virtual elements. In a sense, direct manipulation becomes truly direct thanks to the unification of input and output space. This is generally beneficial for visualization, as illustrated by the natural interaction techniques for stacked graphs by Baur et al. [BLC12].

In terms of lens interaction, especially the adjustment of the geometric properties discussed in Section 2.2 becomes natural and does not require additional widgets. Manipulations (translation, scaling, or rotation) can be accomplished by direct interaction through multi-touch gestures and no menu widgets are necessary for this part. Hence, the user can fully concentrate on the vital aspects – the lens function and its effect on the visualized data. However, one limitation of touch interaction is the *fat-finger problem* [VTS*09], which describes the ambiguity in position that arises from the imprint of the soft fingertip together with the occlusion of the target object by the finger. Hence, pixel-precise positioning of touch requires additional interaction concepts. Different solutions have been developed to overcome this problem (e.g. in [BWB06]) by using an offset between finger and cursor, interfering with the directness of the interaction, or use of digital pens for smaller contact input.

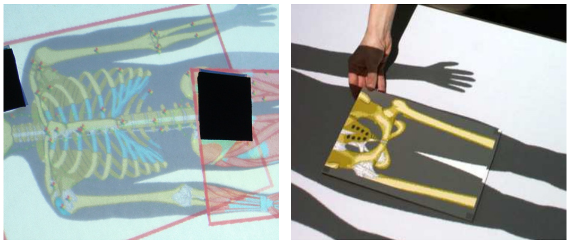
Schmidt et al. [SNDC10] address interaction with node-link-diagrams by designing touch gestures for edge manipulation and incorporate the creation and manipulation of their *PushLens* through touch. The *PushLens* can be created by using three touches close in space and time and can then be repositioned and resized by touch dragging and pinching on the border. Rzeszotarski and Kittur [RK14] also use multi-touch when positioning their physics-based lens for highlighting elements.

As opposed to mouse-based interaction which is always one-handed, natural interactions may allow usage of two-handed, multi-touch interactions. Bimanual interaction concepts for lenses are employed in the *FingerGlass* approach [KAP11], which is shown in Figure 9(a). In *FingerGlass*, the selected region of interest is separated from the output view. Both can be interacted with through touch. This technique specifically supports precise object selection and translation. While one hand manipulates the region of interest, elements within the magnified view of the region can be manipulated by the second hand. To our knowledge, multi-touch interaction techniques for the setting of parameters related to the lens function have not been examined using touch interaction before.

4.3. Tangible Interaction

Ishii and Ullmer [IU97] coined the term tangible interaction as early as 1997. The idea was to use the affordances, tangibility, and manipulability of physical objects for an improved interaction with virtual data. Typically, tangibles are used on interactive tabletops to facilitate tracking possibilities and use the space around the tangible for context visualizations. Because of their properties, tangibles can be moved quickly within the reachable area, often even without visual focus, especially for positioning and change in orientation in a seamless and fluent way.

Kim and Elmqvist present *embodied lenses* [KE12], thin transparencies, that function as additional layers on data similar to *PaperLens* [SSD09]. These tangibles can use physical interactions, such as grasping, placing and moving for creation and manipulation of the lens. Combination of lenses with different functions is also possible as multiple tangibles can be placed on top of each other. Applications include



(a) Lens transparencies (b) Paper lenses

Figure 10: *Tangible interaction with tracked lenses on interactive tabletops: (a)* Embodied lenses *[KE12] utilize translucent light from the tabletop; (b)* PaperLens *[SSD09] uses projection on paper.*

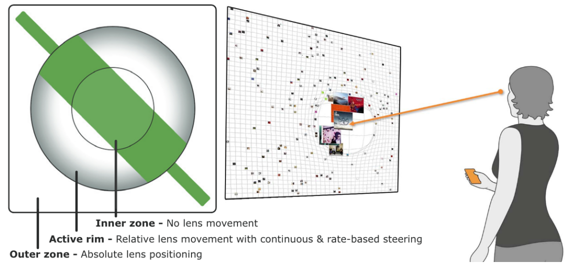


Figure 11: *Gaze-based interaction: The position of the gaze will move the magnification lens in outer or border regions only, allowing for examination of the lens content [SD13, SSND11].*

the exlporation of layered data, for example data on the human skeleton and nerve system in medical imaging as shown in Figure 10(a), as well as multidimensional data visualizations, and tangible map interactions.

Ebert et al. [EWCP13] introduce lenses in the form of *TangibleRings*, as illustrated in Figure 9(b). These ring-like tangible objects have two major advantages: they do not occlude or blur the underlying content and they allow for touch interaction within the region of interest. Additionally, rings with different radius can be concentrically positioned so that lens functions can be logically combined. Similarly, transparent tangibles can be used as graspable representation of lenses that can be stacked and touched from above to manipulate the visible content below the tangible [BKFD14].

A typical limitation of tangibles is their usually inflexible form. Every manipulation of the tangible's shape or size requires hardware modification. This can be easy, when using transparencies or paper or may involve more complex modifications for other materials such as acrylic glass. Therefore, they might only be applicable in specific application contexts. However, their tangibility and the use of our natural motor skills can help make precise and intuitive manipulations of the lens.

4.4. Tangible Views and Spatial Interaction

Spindler et al. [SSD09] developed tangible views that are passive paper lenses on which information is projected from above, see Figure 10(b). These tangible lenses combine display and interaction in a single "device" as the display becomes the actual input channel and the interaction is lifted up from the table into the third dimension. The spatial configuration of the paper lens in the x-y-plane above the table determines where the lens effect should be applied. The distance to the table is an additional parameter that can be used for interaction. Later on, these lenses were extended to active tablet lenses [SBWD13].

Interaction concepts such as translation and rotation are possible as much as flipping, tilting and shaking the lens, which distinguishes this spatial interaction from interaction with tangibles on tabletops. On the tangible view itself interaction is possible through digital pen or touch. Tangible views have been used for data exploration, such as graph exploration where the distance to the table surface influences the level of abstraction shown in the lens [STSD10]. This use case can be seen in Figure 9(c). Their advantage lies in using the physical coordination and muscle memory of the user to help fast navigation within the interaction space. However, similar to tangibles on tabletops, the limitation of tangible views is their rather fixed size and shape.

Moreover, there are several applications in the field of augmented reality, where smart phones or tablets are used as physical interactive lenses that can be move freely in space [SSRG11, LBC04, BLT*12].

4.5. Gaze-Based Interaction and Head Tracking

On large high-resolution displays, controlling lenses with mouse or tangible interaction is infeasible. Gaze-based interaction techniques are a promising alternative [Jac90]. Magnification lenses are often used to make gaze interaction more precise, not for the interaction with lenses themselves. Examples for local magnification tools based on gaze dwell time are proposed by Lankford [Lan00] and Ashmore et al. [ADS05]. Yet, dwell times prevent quick execution of commands and hence hinder a fluent workflow, because users need to fixate a point for a certain amount of time. Therefore, a second modality is used for explicit interactions, such as selections. Kumar et al. [KPW07] introduce the concept of *look-press-look-release* to solve this problem: Only when a keyboard key is pressed, the viewed region is enlarged.

Stellmach et al. [SSND11] use touch as a second modality for confirmation of selected elements. Because of constant eye movement the positioning of these lenses can be cumbersome. Stellmach et al. [SD13] developed different regions of movement for the fisheye lens, thereby interacting with the lens through gaze. As described in Figure 11, when looking within the inner zone of the lens, no movement is triggered, gaze focus in the "active rim" steers the lens continuously and the outer zone helps make fast, absolute positioning.

In the context of graph exploration, Lehmann et al. [LSST11] use head tracking to allow a user to manipulate a focus+context lens technique by moving in front of a large high-resolution display. The distance to the display influences the level of abstraction presented in the lens and thereby directly adjusts a specific lens parameter. Head-tracking is also used by Spindler et al. when designing *Tangible Windows* [SBD12] to provide a volumetric perception on the elements presented on the tangible views when working in 3D information spaces.

To conclude, the majority of lens techniques known in the visualization literature have been developed for mouse and keyboard interaction in desktop environments. Precise positioning of the lens is usually carried out via mouse interaction and lens parameters are to be set in menus and through keyboard shortcuts. There are first promising studies on natural user interfaces for lens interaction, such as tangible lenses and head-tracking for lenses. However, these approaches mostly focus on the manipulation of the position and the size of lenses. Few novel interaction techniques have been presented in terms of adjustment of other lens parameters. This is one possible direction for future work on interaction for lenses. A more general view on interesting research questions will be given in the next section.

5. Directions for Future Work

Our survey delivered a broad view on existing lenses for different data and different tasks and on different ways of interacting with lenses. This section is to look into the future and to identify directions for further research on interactive lenses in visualization.

Lenses and Interaction Virtually all lenses reviewed in this survey support direct manipulation of the lens position on the screen. Adjusting other properties such as size, shape, or parameters controlling the lens function often needs to be carried out via external controls. Maureen Stone, one of the investigators of Magic Lenses, made an important and thought-provoking statement in her review of an initial draft of our survey: "*[...] the fundamental problem is how you provide the user a quick and easy way to: Position the lens, work through the lens, and (possibly) parameterize the lens.*" We add to her statement the need to flexibly combine lenses to create new lens functions on the fly. Addressing these issues requires more studies on the interaction side of lenses, beyond direct manipulation of their position. Future research has to find new ways of making lenses easy to apply and customize, even when the underlying task is more complicated than simple magnification. Utilizing modern interaction modalities seems to be a promising direction.

Lenses in Novel Visualization Environments Existing lens techniques are usually designed for classic desktop visualization settings with mouse and keyboard interaction. We have also seen that first approaches explore the possibilities offered by modern technology, including touch interaction or gaze-based interaction. Moreover, there are lenses that support visualization in environments with multiple or large high-resolution displays. But these are only first steps toward a better utilization of lenses in novel visualization environments. In addition to taking advantage of modern technology, there is also the need to address typical application scenarios in such environments. A particular direction for future work is the investigation of lenses for collaborative multi-user work in future data analytics workspaces for rich, multifaceted exploration and manipulation of information. This involves investigating user-specific private and shared lenses (see [SCG10] for first examples) as well as combining individual lenses to a greater whole in a joint effort.

Lenses for Exploration and Manipulation The majority of lenses support data exploration in the sense that data is consumed by the user. Yet data manipulation becomes more and more important. Data intensive work often involves data correction, data abstraction, data transformation, or in general terms data manipulation. In such scenarios, the user is the producer of data, a fact that leads to requirements that are different from those for pure exploration tasks. A first lens that addresses the problem of data editing is the *EditLens* [GSE*14]. To establish lenses more broadly as tools not only for data exploration, but also for data manipulation, further research is needed. The basic manipulation operations insert, update, and delete must be studied and refined in the context of the different types of data that are relevant for visual data editing. New editing lenses have to take into account the specific characteristics of the data and the requirements of the data manipulation objective.

Lenses as Universal Tools Our survey already indicates that lenses are broadly applicable in visualization. In the *big data* era, we expect lenses to become even more important as versatile tools for working with large and complex datasets. However, wide adoption of lens approaches is currently hindered by the lack of a unified toolkit that can be easily integrated with existing visualization approaches. As of today, lens techniques are tightly interwoven with the base visualization, which makes it difficult to transfer existing solutions to related problems. So an important goal for future research is to come up with concepts and methods that facilitate *implement-once-and-reuse-many-times* development of lens techniques. A long-term goal could be to develop lenses that are deployable in terms of lenses as a service to flexibly enrich the capabilities of existing visual interfaces for data-intensive work.

6. Conclusion

In this work, we surveyed the literature on interactive lenses in visualization. We introduced a conceptual model of lenses that defines them as additional lens pipelines that are attached to a base visualization pipeline. In the sense of this model, a visualization lens can take effect at any stage of the transformation from the raw data to their visual representation. The wide applicability of lenses was illustrated by a systematic view on interactive lens techniques where we categorized lenses according to the specific type of data they address and the user tasks they support. Actual designs of interaction for lenses have been described in the light of classic and modern output devices and interaction modalities.

In addition to our review of existing work, we took a look into the future and identified promising directions for further research on lenses in visualization. We hope that our survey can stimulate not only a broader utilization of existing lenses, but also motivate researchers to investigate novel concepts and techniques that manifest lenses as rich and flexible tools for visual exploration and manipulation.

References

[ACP10] APPERT C., CHAPUIS O., PIETRIGA E.: High-Precision Magnification lenses. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (2010), ACM Press, pp. 273–282. doi:10.1145/1753326.1753366. 8, 9, 10, 19

[ADS05] ASHMORE M., DUCHOWSKI A. T., SHOEMAKER G.: Efficient Eye Pointing with a Fisheye Lens. In *Proc. of Graphics Interface Conference (GI)* (2005), Canadian Human-Computer Communications Society, pp. 203–210. URL: http://dl.acm.org/citation.cfm?id=1089508.1089542. 12, 20

[BCN11] BROSZ J., CARPENDALE M. S. T., NACENTA M. A.: The Undistort Lens. *Computer Graphics Forum 30*, 3 (2011), 881–890. doi:10.1111/j.1467-8659.2011.01937.x. 19

[BCPS02] BAKER C. A. H., CARPENDALE M. S. T., PRUSINKIEWICZ P., SURETTE M. G.: GeneVis: Visualization Tools for Genetic Regulatory Network Dynamics. In *Proc. of IEEE Visualization Conference (Vis)* (2002), IEEE Computer Society, pp. 243–250. doi:10.1109/VISUAL.2002.1183781. 9, 10, 18

[BDW*08] BUTKIEWICZ T., DOU W., WARTELL Z., RIBARSKY W., CHANG R.: Multi-Focused Geospatial Analysis Using Probes. *IEEE Transactions on Visualization and Computer Graphics 14*, 6 (2008), 1165–1172. doi:10.1109/TVCG.2008.149. 19

[BEK*03] BLENKHORN P., EVANS G., KING A., HASTUTI KURNIAWAN S., SUTCLIFFE A.: Screen Magnifiers: Evolution and Evaluation. *Computer Graphics and Applications 23*, 5 (2003), 54–61. doi:10.1109/MCG.2003.1231178. 19

[Ber81] BERTIN J.: *Graphics and Graphic Information-Processing*. de Gruyter, 1981. 1

[BGM*10] BRUCKNER S., GRÖLLER M. E., MUELLER K., PREIM B., SILVER D.: Illustrative Focus+Context Approaches in Interactive Volume Visualization. In *Scientific Visualization: Advanced Concepts*, Hagen H., (Ed.). Schloss Dagstuhl – Leibniz-Zentrum für Informatik, 2010, pp. 136–162. doi:10.4230/DFU.SciViz.2010.136. 19

[BKFD14] BÜSCHEL W., KISTER U., FRISCH M., DACHSELT R.: T4 - Transparent and Translucent Tangibles on Tabletops. In *Proc. of Working Conference on Advanced Visual Interfaces (AVI)* (2014), ACM Press. doi:10.1145/2598153.2598179. 12, 20

[BLC12] BAUR D., LEE B., CARPENDALE S.: TouchWave: Kinetic Multi-touch Manipulation for Hierarchical Stacked Graphs. In *Proc. of International Conference on Interactive Tabletops and Surfaces (ITS)* (2012), ACM Press, pp. 255–264. doi:10.1145/2396636.2396675. 11, 20

[BLT*12] BARIČEVIĆ D., LEE C., TURK M., HÖLLERER T., BOWMAN D. A.: A Hand-Held AR Magic Lens with User-Perspective Rendering. In *Proc. of IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (2012), IEEE Computer Society, pp. 197–206. doi:10.1109/ISMAR.2012.6402557. 12, 19

[BRL09] BERTINI E., RIGAMONTI M., LALANNE D.: Extended Excentric Labeling. *Computer Graphics Forum 28*, 3 (2009), 927–934. doi:10.1111/j.1467-8659.2009.01456.x. 4, 5, 6, 9, 11, 18

[BSF*94] BIER E. A., STONE M. C., FISHKIN K. P., BUXTON W., BAUDEL T.: A Taxonomy of See-Through Tools. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (1994), ACM Press, pp. 358–364. doi:10.1145/191666.191786. 2, 19

[BSP*93] BIER E. A., STONE M. C., PIER K., BUXTON W., DEROSE T. D.: Toolglass and Magic Lenses: the See-Through Interface. In *Proc. of Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH)* (1993), ACM Press, pp. 73–80. doi:10.1145/166117.166126. 2, 3, 19

[BSP97] BIER E., STONE M., PIER K.: Enhanced Illustration Using Magic Lens Filters. *Computer Graphics and Applications 17*, 6 (1997), 62–70. doi:10.1109/38.626971. 2, 19

[BWB06] BENKO H., WILSON A. D., BAUDISCH P.: Precise selection techniques for multi-touch screens. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (2006), ACM Press, pp. 1263–1272. doi:10.1145/1124772.1124963. 11, 20

[CC13] CHANG M.-W., COLLINS C.: Exploring Entities in Text with Descriptive Non-Photorealistic Rendering. In *Proc. of IEEE Pacific Visualization Symposium (PacificVis)* (2013), IEEE Computer Society, pp. 9–16. doi:10.1109/PacificVis.2013.6596122. 8, 9, 18

[CCF97] CARPENDALE M., COWPERTHWAITE D., FRACCHIA F.: Extending Distortion Viewing from 2D to 3D. *Computer Graphics and Applications 17*, 4 (1997), 42–51. doi:10.1109/38.595268. 6, 19

[CKB08] COCKBURN A., KARLSON A., BEDERSON B. B.: A Review of Cverview+Detail, Zooming, and Focus+Context Interfaces. *ACM Computing Surveys 41*, 1 (2008), 2:1–2:31. doi:10.1145/1456650.1456652. 1, 19

[CLP04] CARPENDALE S., LIGH J., PATTISON E.: Achieving Higher Magnification in Context. In *Proc. of ACM Symposium on User Interface Software and Technology (UIST)* (2004), ACM Press, pp. 71–80. doi:10.1145/1029632.1029645. 7, 19

[CM01] CARPENDALE M. S. T., MONTAGNESE C.: A Framework for Unifying Presentation Space. In *Proc. of ACM Symposium on User Interface Software and Technology (UIST)* (2001), ACM Press, pp. 61–70. doi:10.1145/502348.502358. 7, 20

[CMS94] CIGNONI P., MONTANI C., SCOPIGNO R.: MagicSphere: an Insight Tool for 3D Data Visualization. *Computer Graphics Forum 13*, 3 (1994), 317–328. doi:10.1111/1467-8659.1330317. 9, 18

[CMS99] CARD S., MACKINLAY J., SHNEIDERMAN B.: *Readings in Information Visualization: Using Vision to Think*. Morgan Kaufmann, 1999. 3, 20

[EBD05] ELLIS G., BERTINI E., DIX A.: The Sampling Lens: Making Sense of Saturated Visualisations. In *CHI Extended Abstracts on Human Factors in Computing Systems* (2005), ACM Press, pp. 1351–1354. doi:10.1145/1056808.1056914. 7, 9, 11, 18

[EBZ*12] ENDERT A., BRADEL L., ZEITZ J., ANDREWS C., NORTH C.: Designing Large High-resolution Display Workspaces. In *Proc. of Working Conference on Advanced Visual Interfaces (AVI)* (2012), ACM Press, pp. 58–65. doi:10.1145/2254556.2254570. 10, 20

[ED06a] ELLIS G., DIX A. J.: Enabling Automatic Clutter Reduction in Parallel Coordinate Plots. *IEEE Transactions on Visualization and Computer Graphics 12*, 5 (2006), 717–724. doi:10.1109/TVCG.2006.138. 7, 9, 10, 18

[ED06b] ELLIS G., DIX A. J.: The Plot, the Clutter, the Sampling and its Lens: Occlusion Measures for Automatic Clutter Reduction. In *Proc. of Working Conference on Advanced Visual Interfaces (AVI)* (2006), ACM Press, pp. 266–269. doi:10.1145/1133265.1133318. 4, 5, 7, 9, 18

[EDF11] ELMQVIST N., DRAGICEVIC P., FEKETE J.-D.: Color Lens: Adaptive Color Scale Optimization for Visual Exploration. *IEEE Transactions on Visualization and Computer Graphics 17*, 6 (2011), 795–807. doi:10.1109/TVCG.2010.94. 8, 9, 18

[Elm05] ELMQVIST N.: BalloonProbe: Reducing Occlusion in 3D Using Interactive Space Distortion. In *Proc. of ACM Symposium on Virtual Reality Software and Technology (VRST)* (2005), ACM Press, pp. 134–137. doi:10.1145/1101616.1101643. 19

[EWCP13] EBERT A., WEBER C., CERNEA D., PETSCH S.: TangibleRings: Nestable Circular Tangibles. In *CHI Extended Abstracts on Human Factors in Computing Systems* (2013), ACM Press, pp. 1617–1622. doi:10.1145/2468356.2468645. 10, 12, 20

[FG98] FUHRMANN A., GRÖLLER E.: Real-time Techniques for 3D Flow Visualization. In *Proc. of IEEE Visualization Conference (Vis)* (1998), IEEE Computer Society, pp. 305–312. doi:10.1109/VISUAL.1998.745317. 6, 7, 9, 11, 18

[Fox98] FOX D.: Composing Magic Lenses. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (1998), ACM Press, pp. 519–525. doi:10.1145/274644.274714. 5, 20

[FP99] FEKETE J.-D., PLAISANT C.: Excentric Labeling: Dynamic Neighborhood Labeling for Data Visualization. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (1999), ACM Press, pp. 512–519. doi:10.1145/302979.303148. 9, 18

[FS92] FEINER S. K., SELIGMANN D. D.: Cutaways and Ghosting: Satisfying Visibility Constraints in Dynamic 3D Illustrations. *The Visual Computer 8*, 5–6 (1992), 292–302. doi:10.1007/BF01897116. 19

[FS95] FISHKIN K. P., STONE M. C.: Enhanced Dynamic Queries via Movable Filters. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (1995), ACM Press, pp. 415–420. doi:10.1145/223904.223960. 2, 20

[FS05] FORLINES C., SHEN C.: DTLens: Multi-user Tabletop Spatial Data Exploration. In *Proc. of ACM Symposium on User Interface Software and Technology (UIST)* (2005), ACM Press, pp. 119–122. doi:10.1145/1095034.1095055. 7, 19

[Fur86] FURNAS G. W.: Generalized Fisheye Views. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (1986), ACM Press, pp. 16–23. doi:10.1145/22627.22342. 2, 20

[GNBP11] GASTEIGER R., NEUGEBAUER M., BEUING O., PREIM B.: The FLOWLENS: A Focus-and-Context Visualization Approach for Exploration of Blood Flow in Cerebral Aneurysms. *IEEE Transactions on Visualization and Computer Graphics 17*, 12 (2011), 2183–2192. doi:10.1109/TVCG.2011.243. 6, 9, 18

[GSE*14] GLADISCH S., SCHUMANN H., ERNST M., FÜLLEN G., TOMINSKI C.: Semi-Automatic Editing of Graphs with Customized Layouts. *Computer Graphics Forum 33*, 3 (2014). (to appear). 13, 19

[Gut02] GUTWIN C.: Improving Focus Targeting in Interactive Fisheye Views. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (2002), ACM Press, pp. 267–274. doi:10.1145/503376.503424. 19

[Hau06] HAUSER H.: Generalizing Focus+Context Visualization. In *Scientific Visualization: The Visual Extraction of Knowledge from Data*, Bonneau G.-P., Ertl T., Nielson G., (Eds.). Springer, 2006, pp. 305–327. doi:10.1007/3-540-30790-7_18. 1, 20

[HLTE11] HEIM P., LOHMANN S., TSENDRAGCHAA D., ERTL T.: SemLens: Visual Analysis of Semantic Data with Scatter Plots and Semantic Lenses. In *Proc. of International Conference on Semantic Systems* (2011), ACM Press, pp. 175–178. doi:10.1145/2063518.2063543. 9, 19

[HRS97] HUDSON S. E., RODENSTEIN R., SMITH I.: Debugging Lenses: A New Class of Transparent Tools for User Interface Debugging. In *Proc. of ACM Symposium on User Interface Software and Technology (UIST)* (1997), ACM Press, pp. 179–187. doi:10.1145/263407.263542. 19

[HS04] HOCHHEISER H., SHNEIDERMAN B.: Dynamic Query Tools for Time Series Data Sets: Timebox Widgets for Interactive Exploration. *Information Visualization 3*, 1 (2004), 1–18. doi:10.1145/993176.993177. 19

[HTE11] HURTER C., TELEA A., ERSOY O.: MoleView: An Attribute and Structure-Based Semantic Lens for Large Element-Based Plots. *IEEE Transactions on Visualization and Computer Graphics 17*, 12 (2011), 2600–2609. doi:10.1109/TVCG.2011.223. 9, 11, 19

[IIH*13] ISENBERG P., ISENBERG T., HESSELMANN T., LEE B., VON ZADOW U., TANG A.: Data Visualization on Interactive Surfaces: A Research Agenda. *Computer Graphics and Applications 33*, 2 (2013), 16–24. doi:10.1109/MCG.2013.24. 10, 20

[IU97] ISHII H., ULLMER B.: Tangible Bits: Towards Seamless Interfaces Between People, Bits and Atoms. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (1997), ACM Press, pp. 234–241. doi:10.1145/258549.258715. 11, 20

[Jac90] JACOB R. J. K.: What You Look at is What You Get: Eye Movement-based Interaction Techniques. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (1990), ACM Press, pp. 11–18. doi:10.1145/97243.97246. 12, 20

[JDK10] JUSUFI I., DINGJIE Y., KERREN A.: The Network Lens: Interactive Exploration of Multivariate Networks Using Visual Filtering. In *Proc. of International Conference Information

Visualisation (IV) (2010), IEEE Computer Society, pp. 35–42. doi:10.1109/IV.2010.15. 9, 11, 19

[KAP11] Käser D. P., Agrawala M., Pauly M.: FingerGlass: Efficient Multiscale Interaction on Multitouch Screens. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (2011), ACM Press, pp. 1601–1610. doi:10.1145/1978942.1979175. 10, 11, 20

[KCJ*10] Karnick P., Cline D., Jeschke S., Razdan A., Wonka P.: Route Visualization Using Detail Lenses. *IEEE Transactions on Visualization and Computer Graphics 16*, 2 (2010), 235–247. doi:10.1109/TVCG.2009.65. 7, 9, 19

[KE12] Kim K., Elmqvist N.: Embodied Lenses for Collaborative Visual Queries on Tabletop Displays. *Information Visualization 11*, 4 (2012), 319–338. doi:10.1177/1473871612441874. 11, 12, 20

[Kea98] Keahey A.: The Generalized Detail-In-Context Problem. In *Proc. of IEEE Symposium Information Visualization (InfoVis)* (1998), IEEE Computer Society, pp. 44–51. doi:10.1109/INFVIS.1998.729558. 7, 20

[KFA*04] Khan A., Fitzmaurice G. W., Almeida D., Burtnyk N., Kurtenbach G.: A Remote Control Interface for Large Displays. In *Proc. of ACM Symposium on User Interface Software and Technology (UIST)* (2004), ACM Press, pp. 127–136. doi:10.1145/1029632.1029655. 19

[Kin10] Kincaid R.: SignalLens: Focus+Context Applied to Electronic Time Series. *IEEE Transactions on Visualization and Computer Graphics 16*, 6 (2010), 900–907. doi:10.1109/TVCG.2010.193. 5, 6, 9, 19

[KMS07] Kalkofen D., Méndez E., Schmalstieg D.: Interactive Focus and Context Visualization for Augmented Reality. In *Proc. of IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (2007), IEEE Computer Society, pp. 191–201. doi:10.1109/ISMAR.2007.4538846. 19

[KPW07] Kumar M., Paepcke A., Winograd T.: EyePoint: Practical Pointing and Selection Using Gaze and Keyboard. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (2007), ACM Press, pp. 421–430. doi:10.1145/1240624.1240692. 12, 20

[KR96] Keahey A., Robertson E. L.: Techniques for Nonlinear Magnification Transformations. In *Proc. of IEEE Symposium Information Visualization (InfoVis)* (1996), IEEE Computer Society, pp. 38–45. doi:10.1109/INFVIS.1996.559214. 20

[KTW*13] Krüger R., Thom D., Wörner M., Bosch H., Ertl T.: TrajectoryLenses - A Set-based Filtering and Exploration Technique for Long-term Trajectory Data. *Computer Graphics Forum 32*, 3 (2013), 451–460. doi:10.1111/cgf.12132. 8, 9, 19

[LA94] Leung Y. K., Apperley M. D.: A Review and Taxonomy of Distortion-oriented Presentation Techniques. *ACM Transactions on Computer-Human Interaction 1*, 2 (1994), 126–160. doi:10.1145/180171.180173. 1, 2, 3, 20

[Lan00] Lankford C.: Effective Eye-gaze Input into Windows. In *Proc. of Symposium on Eye Tracking Research & Applications* (2000), ACM Press, pp. 23–27. doi:10.1145/355017.355021. 12, 20

[LBC04] Looser J., Billinghurst M., Cockburn A.: Through the Looking Glass: The Use of Lenses As an Interface Tool for Augmented Reality Interfaces. In *Proc. of International Conference on Computer Graphics and Interactive Techniques in Australasia and South East Asia (GRAPHITE)* (2004), ACM Press, pp. 204–211. doi:10.1145/988834.988870. 12, 20

[LGB07] Looser J., Grasset R., Billinghurst M.: A 3D Flexible and Tangible Magic Lens in Augmented Reality. In *Proc. of IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (2007), IEEE Computer Society, pp. 51–54. doi:10.1109/ISMAR.2007.4538825. 6, 20

[LHJ01] LaMar E., Hamann B., Joy K.: A magnification lens for interactive volume visualization. In *Proc. of Pacific Conference on Computer Graphics and Applications (PCCGA)* (2001), IEEE Computer Society, pp. 223–232. doi:10.1109/PCCGA.2001.962877. 6, 9, 19

[LRA*07] Li W., Ritter L., Agrawala M., Curless B., Salesin D.: Interactive Cutaway Illustrations of Complex 3D Models. *ACM Transactions on Graphics 26*, 3 (2007), 31–1–31–11. doi:10.1145/1276377.1276416. 19

[LSST11] Lehmann A., Schumann H., Staadt O., Tominski C.: Physical Navigation to Support Graph Exploration on a Large High-Resolution Display. In *Advances in Visual Computing*, Bebis G., Boyle R., Parvin B., Koracin D., Wang S., Kyungnam K., Benes B., Moreland K., Borst C., DiVerdi S., Yi-Jen C., Ming J., (Eds.), vol. 6938 of *Lecture Notes in Computer Science*. Springer, 2011, pp. 496–507. doi:10.1007/978-3-642-24028-7_46. 13, 20

[LWG11] Lambeck C., Wojdziak J., Groh R.: Facet Lens: Local Exploration and Discovery in Globally Faceted Data Sets. In *Proc. of Conference on Creativity and Innovation in Design (DESIRE)* (2011), ACM Press, pp. 85–88. doi:10.1145/2079216.2079228. 9, 19

[MCH*09] Moscovich T., Chevalier F., Henry N., Pietriga E., Fekete J.-D.: Topology-aware Navigation in Large Networks. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (2009), ACM Press, pp. 2319–2328. doi:10.1145/1518701.1519056. 8, 9, 19

[MTHG03] Mattausch O., Theussl T., Hauser H., Gröller E.: Strategies for Interactive Exploration of 3D Flow Using Evenly-spaced Illuminated Streamlines. In *Proc. of Spring Conference on Computer Graphics (SCCG)* (2003), ACM Press, pp. 213–222. doi:10.1145/984952.984987. 9, 19

[Neu03] Neumann P.: *Taxonomy for Discrete Lenses*. Technical report no. 2003-734-37, Department of Computer Science, University of Calgary, 2003. 20

[NIC07] Neumann P., Isenberg T., Carpendale M. S. T.: NPR Lenses: Interactive Tools for Non-Photorealistic Line Drawings. In *Proc. of Smart Graphics (SG)* (2007), Springer, pp. 10–22. doi:10.1007/978-3-540-73214-3_2. 19

[PA08] Pietriga E., Appert C.: Sigma Lenses: Focus-Context Transitions Combining Space, Time and Translucence. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (2008), ACM Press, pp. 1343–1352. doi:10.1145/1357054.1357264. 19

[PBA10] Pietriga E., Bau O., Appert C.: Representation-Independent In-Place Magnification with Sigma Lenses. *IEEE Transactions on Visualization and Computer Graphics 16*, 3 (2010), 455–467. doi:10.1109/TVCG.2009.98. 19

[PBKE11] Panagiotidis A., Bosch H., Koch S., Ertl T.: EdgeAnalyzer: Exploratory Analysis through Advanced Edge Interaction. In *Proc. of Hawaii International Conference on System Sciences (HICSS)* (2011), IEEE Computer Society. doi:10.1109/HICSS.2011.178. 9, 19

[PPCP12] Pindat C., Pietriga E., Chapuis O., Puech C.: JellyLens: Content-aware Adaptive Lenses. In *Proc. of ACM Symposium on User Interface Software and Technology (UIST)* (2012), ACM Press, pp. 261–270. doi:10.1145/2380116.2380150. 5, 6, 7, 9, 10, 19

[PPCP13] PINDAT C., PIETRIGA E., CHAPUIS O., PUECH C.: Drilling into Complex 3D Models with Gimlenses. In *Proc. of ACM Symposium on Virtual Reality Software and Technology (VRST)* (2013), ACM Press, pp. 223–230. doi:10.1145/2503713.2503714. 9, 11, 19

[RC94] RAO R., CARD S. K.: The Table Lens: Merging Graphical and Symbolic Representations in an Interactive Focus + Context Visualization for Tabular Information. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (1994), ACM Press, pp. 318–322. doi:10.1145/191666.191776. 6, 9, 19

[RCBBL07] RAMOS G., COCKBURN A., BALAKRISHNAN R., BEAUDOUIN-LAFON M.: Pointing Lenses: Facilitating Stylus Input Through Visual-and Motor-space Magnification. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (2007), ACM Press, pp. 757–766. doi:10.1145/1240624.1240741. 19

[RH04] ROPINSKI T., HINRICHS K.: Real-Time Rendering of 3D Magic Lenses Having Arbitrary Convex Shapes. In *Proc. of International Conference in Central Europe on Computer Graphics, Visualization and Computer Vision (WSCG)* (2004), UNION Agency - Science Press, pp. 379–386. 6, 20

[RHS05] ROPINSKI T., HINRICHS K. H., STEINICKE F.: A Solution for the Focus and Context Problem in Geo-Virtual Environments. In *Proc. of ISPRS Workshop on Dynamic and Multi-dimensional GIS (DMGIS)* (2005), pp. 144–149. 9, 19

[RK14] RZESZOTARSKI J. M., KITTUR A.: Kinetica: Naturalistic Multi-touch Data Visualization. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (2014), ACM Press. (to appear). 11, 20

[RLE05] RYALL K., LI Q., ESENTHER A.: Temporal Magic Lens: Combined Spatial and Temporal Query and Presentation. In *Proc. of IFIP TC13 Conference on Human-Computer Interaction (INTERACT)* (2005), Springer, pp. 809–822. doi:10.1007/11555261_64. 9, 19

[RM93] ROBERTSON G. G., MACKINLAY J. D.: The Document Lens. In *Proc. of ACM Symposium on User Interface Software and Technology (UIST)* (1993), ACM Press, pp. 101–108. doi:10.1145/168642.168652. 9, 11, 19

[Rob07] ROBERTS J.: State of the Art: Coordinated Multiple Views in Exploratory Visualization. In *Proc. of International Conference on Coordinated and Multiple Views in Exploratory Visualization (CMV)* (2007), IEEE Computer Society, pp. 61–71. doi:10.1109/CMV.2007.20. 1, 20

[SB92] SARKAR M., BROWN M. H.: Graphical Fisheye Views of Graphs. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (1992), ACM Press, pp. 83–91. doi:10.1145/142750.142763. 9, 19

[SB94] SARKAR M., BROWN M. H.: Graphical Fisheye Views. *Communications of the ACM 37*, 12 (1994), 73–83. doi:10.1145/198366.198384. 9, 19

[SBD12] SPINDLER M., BÜSCHEL W., DACHSELT R.: Use Your Head: Tangible Windows for 3D Information Spaces in a Tabletop Environment. In *Proc. of International Conference on Interactive Tabletops and Surfaces (ITS)* (2012), ACM Press, pp. 245–254. doi:10.1145/2396636.2396674. 13, 20

[SBWD13] SPINDLER M., BÜSCHEL W., WINKLER C., DACHSELT R.: Tangible Displays for the Masses: Spatial Interaction with Handheld Displays by Using Consumer Depth Cameras. *Personal and Ubiquitous Computing* (2013). doi:10.1007/s00779-013-0730-7. 12, 20

[SCG10] SCHMIDT D., CHONG M. K., GELLERSEN H.: IdLenses: Dynamic Personal Areas on Shared Surfaces. In *Proc. of International Conference on Interactive Tabletops and Surfaces (ITS)* (2010), ACM Press, pp. 131–134. doi:10.1145/1936652.1936678. 13, 19

[SD13] STELLMACH S., DACHSELT R.: Still Looking: Investigating Seamless Gaze-supported Selection, Positioning, and Manipulation of Distant Targets. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (2013), ACM Press, pp. 285–294. doi:10.1145/2470654.2470695. 12, 20

[SFB94] STONE M. C., FISHKIN K. P., BIER E. A.: The Movable Filter as a User Interface Tool. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (1994), ACM Press, pp. 306–312. doi:10.1145/191666.191774. 2, 20

[SFR01] STOEV S. L., FEURER M., RUCKABERLE M.: Exploring the Past: A Toolset for Visualization of Historical Events in Virtual Environments. In *Proc. of ACM Symposium on Virtual Reality Software and Technology (VRST)* (2001), ACM Press, pp. 63–70. doi:10.1145/505008.505020. 9, 19

[SHER99] SHAW C. D., HALL J. A., EBERT D. S., ROBERTS D. A.: Interactive Lens Visualization Techniques. In *Proc. of IEEE Visualization Conference (Vis)* (1999), IEEE Computer Society, pp. 155–160. doi:10.1109/VISUAL.1999.809882. 9, 19

[Shn83] SHNEIDERMAN B.: Direct Manipulation: A Step Beyond Programming Languages. *IEEE Computer 16*, 8 (1983), 57–69. doi:10.1109/MC.1983.1654471. 6, 20

[Shn96] SHNEIDERMAN B.: The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations. In *Proc. of IEEE Symposium on Visual Languages (VL)* (1996), IEEE Computer Society, pp. 336–343. 3, 7, 20

[SNDC10] SCHMIDT S., NACENTA M. A., DACHSELT R., CARPENDALE S.: A Set of Multi-Touch Graph Interaction Techniques. In *Proc. of International Conference on Interactive Tabletops and Surfaces (ITS)* (2010), ACM Press, pp. 113–116. doi:10.1145/1936652.1936673. 7, 9, 11, 19

[SSD09] SPINDLER M., STELLMACH S., DACHSELT R.: PaperLens: Advanced Magic Lens Interaction Above the Tabletop. In *Proc. of International Conference on Interactive Tabletops and Surfaces (ITS)* (2009), ACM Press, pp. 69–76. doi:10.1145/1731903.1731920. 6, 11, 12, 20

[SSND11] STELLMACH S., STOBER S., NÜRNBERGER A., DACHSELT R.: Designing Gaze-supported Multimodal Interactions for the Exploration of Large Image Collections. In *Proc. of 1st Conference on Novel Gaze-Controlled Applications* (2011), ACM Press, pp. 1:1–1:8. doi:10.1145/1983302.1983303. 12, 20

[SSRG11] SÖRÖS G., SEICHTER H., RAUTEK P., GRÖLLER E.: Augmented Visualization with Natural Feature Tracking. In *Proc. of International Conference on Mobile and Ubiquitous Multimedia (MUM)* (2011), ACM Press, pp. 4–12. doi:10.1145/2107596.2107597. 12, 20

[SSS02] STOEV S. L., SCHMALSTIEG D., STRASSER W.: The Through-the-Lens Metaphor: Taxonomy and Application. In *Proc. of IEEE Virtual Reality Conference (VR)* (2002), IEEE Computer Society, pp. 285–286. doi:10.1109/VR.2002.996541. 20

[STSD10] SPINDLER M., TOMINSKI C., SCHUMANN H., DACHSELT R.: Tangible Views for Information Visualization. In *Proc. of International Conference on Interactive Tabletops and Surfaces (ITS)* (2010), ACM Press, pp. 157–166. doi:10.1145/1936652.1936684. 8, 9, 10, 12, 19

[TAS09] TOMINSKI C., ABELLO J., SCHUMANN H.: CGV – An

Interactive Graph Visualization System. *Computers & Graphics 33*, 6 (2009), 660–678. doi:10.1016/j.cag.2009.06.002. 4, 5, 8, 9, 19

[TAvHS06] TOMINSKI C., ABELLO J., VAN HAM F., SCHUMANN H.: Fisheye Tree Views and Lenses for Graph Visualization. In *Proc. of International Conference Information Visualisation (IV)* (2006), IEEE Computer Society, pp. 17–24. doi:10.1109/IV.2006.54. 4, 5, 6, 9, 10, 19

[TFS08] THIEDE C., FUCHS G., SCHUMANN H.: Smart Lenses. In *Proc. of Smart Graphics (SG)* (2008), Springer, pp. 178–189. doi:10.1007/978-3-540-85412-8_16. 4, 5, 19

[TGBD08] TRAPP M., GLANDER T., BUCHHOLZ H., DOLNER J.: 3D Generalization Lenses for Interactive Focus + Context Visualization of Virtual City Models. In *Proc. of International Conference Information Visualisation (IV)* (2008), IEEE Computer Society, pp. 356–361. doi:10.1109/IV.2008.18. 9, 19

[Tom11] TOMINSKI C.: Event-Based Concepts for User-Driven Visualization. *Information Visualization 10*, 1 (2011), 65–81. doi:10.1057/ivs.2009.32. 6, 20

[TSAA12] TOMINSKI C., SCHUMANN H., ANDRIENKO G., ANDRIENKO N.: Stacking-Based Visualization of Trajectory Attribute Data. *IEEE Transactions on Visualization and Computer Graphics 18*, 12 (2012), 2565–2574. doi:10.1109/TVCG.2012.265. 4, 5, 9, 19

[UvK13] UKROP J., ČÍKOVÁ Z., KAPEC P.: Visual Access to Graph Content Using Magic Lenses and Filtering. In *Proc. of Spring Conference on Computer Graphics (SCCG)* (2013), ACM Press, pp. 23–30. doi:10.1145/2448531.2448534. 9, 19

[VCWP96] VIEGA J., CONWAY M., WILLIAMS G. H., PAUSCH R. F.: 3D Magic Lenses. In *Proc. of ACM Symposium on User Interface Software and Technology (UIST)* (1996), ACM Press, pp. 51–58. doi:10.1145/237091.237098. 9, 19

[vHvW04] VAN HAM F., VAN WIJK J.: Interactive Visualization of Small World Graphs. In *Proc. of IEEE Symposium Information Visualization (InfoVis)* (2004), IEEE Computer Society, pp. 199–206. doi:10.1109/INFVIS.2004.43. 8, 9, 19

[VKG04] VIOLA I., KANITSAR A., GRÖLLER M. E.: Importance-Driven Volume Rendering. In *Proc. of IEEE Visualization Conference (Vis)* (2004), IEEE Computer Society, pp. 139–145. doi:10.1109/VISUAL.2004.48. 19

[VTS*09] VOIDA S., TOBIASZ M., STROMER J., ISENBERG P., CARPENDALE S.: Getting Practical with Interactive Tabletop Displays: Designing for Dense Data, "Fat Fingers," Diverse Interactions, and Face-to-face Collaboration. In *Proc. of International Conference on Interactive Tabletops and Surfaces (ITS)* (2009), ACM Press, pp. 109–116. doi:10.1145/1731903.1731926. 6, 11, 20

[WCG03] WONG N., CARPENDALE M. S. T., GREENBERG S.: EdgeLens: An Interactive Method for Managing Edge Congestion in Graphs. In *Proc. of IEEE Symposium Information Visualization (InfoVis)* (2003), IEEE Computer Society, pp. 51–58. doi:10.1109/INFVIS.2003.1249008. 7, 9, 10, 19

[WGK10] WARD M., GRINSTEIN G., KEIM D.: *Interactive Data Visualization: Foundations, Techniques, and Applications*. A K Peters, 2010. 1, 20

[WKS07] WALDNER M., KALKUSCH M., SCHMALSTIEG D.: Optical Magic Lenses and Polarization-Based Interaction Techniques. In *Proc. of Workshop on Immersive Projection Technology, Eurographics Workshop on Virtual Enviroments (IPT/EGVE)* (2007), Eurographics Association, pp. 61–68. doi:10.2312/EGVE/IPT_EGVE2007/061-068. 10, 20

[WZMK05] WANG L., ZHAO Y., MUELLER K., KAUFMAN A. E.: The Magic Volume Lens: An Interactive Focus+Context Technique for Volume Rendering. In *Proc. of IEEE Visualization Conference (Vis)* (2005), IEEE Computer Society, p. 47. doi:10.1109/VISUAL.2005.1532818. 7, 9, 19

[YCB05] YANG Y., CHEN J., BEHESHTI M.: Nonlinear Perspective Projections and Magic Lenses: 3D View Deformation. *Computer Graphics and Applications 25*, 1 (2005), 76–84. doi:10.1109/MCG.2005.29. 20

[YKSJ07] YI J. S., KANG Y. A., STASKO J., JACKO J.: Toward a Deeper Understanding of the Role of Interaction in Information Visualization. *IEEE Transactions on Visualization and Computer Graphics 13*, 6 (2007), 1224–1231. doi:10.1109/TVCG.2007.70515. 3, 8, 20

[ZCB11] ZHAO J., CHEVALIER F., BALAKRISHNAN R.: KronoMiner: Using Multi-foci Navigation for the Visual Exploration of Time-series Data. In *Proc. of SIGCHI Conference Human Factors in Computing Systems (CHI)* (2011), ACM Press, pp. 1737–1746. doi:10.1145/1978942.1979195. 9, 19

[ZCPB11] ZHAO J., CHEVALIER F., PIETRIGA E., BALAKRISHNAN R.: Exploratory Analysis of Time-Series with ChronoLenses. *IEEE Transactions on Visualization and Computer Graphics 17*, 12 (2011), 2422–2431. doi:10.1109/TVCG.2011.195. 4, 7, 9, 19

[ZZG*12] ZHAO X., ZENG W., GU X. D., KAUFMAN A. E., XU W., MUELLER K.: Conformal Magnifier: A Focus+Context Technique with Local Shape Preservation. *IEEE Transactions on Visualization and Computer Graphics 18*, 11 (2012), 1928–1941. doi:10.1109/TVCG.2012.70. 19

Appendix: Summary of References

This appendix is to list all references that we have at our disposal and provide a brief explaining caption for each of them. The appendix is structured into separate sections covering visualization lenses, lens-like techniques, general-purpose magnification and distortion lenses, miscellaneous lenses, models, concepts & taxonomies, and interaction with lenses.

Visualization Lenses

[BCPS02] Fuzzy Lenses: alternative gene representation; Base Pair Lens: separation of genes; Ring Lens: detail in context view applied to genetic network data.

[BRL09] Enhanced Excentric Labeling: Adaptive lens for labeling data points in scatter plots.

[CC13] Text visualization assisted by interactive lens queries on spatial models.

[CMS94] Magic Sphere: Various lens functions for altering 3D visual representations.

[EBD05, ED06b, ED06a] Sampling Lens: Interactive sampling in scatter plots and parallel coordinates plots.

[EDF11] Color Lens: Locally adapted color coding for visual representations of data and images.

[FG98] Lenses for flow data: Magic lens and magic box for higher-resolution streamline visualization.

[FP99] Excentric Labeling: Labeling points in visual representations of data.

[GNBP11] FlowLens: Visualizing flow data with additional attributes in a 2D lens.

[GSE*14] EditLens: Semi-automatic editing of graphs with customized layouts.
[HLTE11] SemLens: Analyzing scatter plots with combinable semantic lenses.
[HTE11] MoleView: Rearranging graphical primitives of multivariate relational data with lenses.
[JDK10] Network Lens: Representing data attributes in network structures.
[KCJ*10] Detail Lenses: Facilitating the understanding of navigation directions via detail maps for points of interest.
[Kin10] SignalLens: Analyzing details in signal traces with a focus+context approach.
[KTW*13] TrajectoryLenses: Lenses for filtering and exploring trajectory data.
[LHJ01] Lenses for magnifying focus regions in volume data.
[LWG11] Facet Lens: Exploration of document data with multiple facets.
[MCH*09] Bring & Go: Rearranging graph vertices for quick navigation.
[MTHG03] Magic Volumes: Focus+context visualization of 3D flow data.
[PBKE11] EdgeAnalyser: Support edge grouping and insight into properties of groups of edges.
[PPCP12] JellyLens: Lens that adapts its shape to features in visual representations.
[PPCP13] Gimlenses: Drilling holes into complex 3D models to uncover details.
[RC94] Table Lens: Focus+context for tabular visualizations.
[RHS05] Lenses for focus+context in geo-virtual environments.
[RLE05] Temporal Magic Lens: Combining spatial and temporal aspects for visual analysis of video data.
[RM93] Document Lens: Classic lens for document visualization.
[SB92, SB94] Fisheye Views: Classic focus+context with application to visualization.
[SFR01] Time Lens: Comparing different points in time for understanding spatio-temporal data.
[SHER99] Interactive 3D lens: Enhancing 3D glyph-based visual representations.
[SNDC10] PushLens: Routing edges around the lens to reduce ambiguities in graph layouts.
[STSD10] Tangible views: Interactive visualization lenses made tangible.
[TAvHS06, TAS09] Graph lenses: Supporting graph exploration through lens techniques.
[TFS08] Smart lenses: Integrating lenses into the data state reference model of visualization.
[TGBD08] 3D Generalization Lenses: Focus+context visualization of virtual city models.
[TSAA12] Time Lens: Enhancing the visualization of spatial movements with temporal aspects.
[UvK13] Magic lenses for hypergraphs: Querying graph structures with hyperedges using interactive lenses.
[VCWP96] 3D Magic lenses: Extending magic lenses to the third dimension.
[vHvW04] Graph abstraction lens: Combining semantic and geometric distortion for analyzing hierarchical graphs.
[WCG03] EdgeLens: Bending graph edges around a lens to reduce ambiguities.
[WZMK05] The Magic Volume Lens: Magnification of features of interest in volume visualization.
[ZCB11] MagicAnalytics Lens: On-the-fly comparison of time series regarding analytical methods.
[ZCPB11] ChronoLenses: Transform time series on the fly.

Lens-Like Techniques

[BDW*08] Probes for geospatial analysis: Access to details by placing probes on maps.
[BGM*10] Illustrative focus+context: Cutaway views and ghosting for volume visualization.
[Elm05] BalloonProbe: Interactive reduction of occlusion problems in 3D visualization scenes.
[FS92] Cutaways and ghosting: Addressing visibility problems in 3D illustrations.
[HS04] Timeboxes: Movable filter tools for querying time series.
[KFA*04] Frisbee: Remote control interface for large displays.
[LRA*07] Cutaway illustrations of complex 3D models.
[VKG04] Importance-Driven Volume Rendering: Cutaway and ghosting for focus+context.

General-Purpose Magnification and Distortion Lenses

[ACP10] High precision magnification lenses: Improved picking through separation of visual and motor space.
[BCN11] Undistort lens: Locally undistort representations that have been modified by global distortion techniques.
[BEK*03] Screen magnifiers: A review of techniques for magnifying screen content.
[CLP04] Higher magnification: New functions that improve magnification while maintaining context.
[FS05] DTLens: Multi-user, multi-lens magnification on tabletops.
[Gut02] Speed-coupled flattening: Improving focus targeting in fisheye lenses.
[PA08, PBA10] Sigma lenses: Using space, translucence, and time for transitions between focus and context.
[RCBBL07] Pointing Lenses: Easier selection of small targets.
[ZZG*12] Conformal magnifier: Magnification with conformal mapping and local shape preservation.

Miscellaneous Lenses

[BLT*12] AR magic lens: Correct (user) perspective into augmented reality.
[HRS97] Debugging Lenses: Supporting debugging with lens techniques.
[KMS07] AR focus+context visualization: Lenses restrict overlayed context presentation.
[NIC07] NPR Lenses: Lenses with non-photorealistic rendering effects.
[SCG10] IdLenses: Personalization of graphical content through lenses.

Models, Concepts & Taxonomies

[BSF*94] A taxonomy of the See-Through Interface, including Toolglass and Magic Lenses.
[BSP*93] The classic paper on Toolglass and Magic Lenses.
[BSP97] Various Magic Lens filters for illustration systems.
[CCF97] Conceptual considerations when extending 2D distortion to 3D distortion.
[CKB08] Survey on overview+detail, zooming, and focus+context approaches.

[CM01] A unified model for presentation spaces allowing for different presentation methods in a single interface.
[CMS99] Model of the visualization process as a pipeline of data transformation stages.
[EBZ*12] Design considerations for workspaces with large high-resolution displays.
[Fox98] A generic model for composing multiple lens functions via delegation, rather than inheritance.
[FS95] Composing movable filters for enhanced dynamic querying.
[Fur86] The theory behind degree of interest for focus+context approaches.
[Hau06] A generalized view on focus+context in visualization.
[Kea98] Generalization of the focus within context problem.
[KR96] Functions for non-linear magnification transformations.
[LA94] A survey on distortion-oriented presentation techniques.
[Neu03] A taxonomy and review of discrete lens techniques.
[RH04] An implementation model for 3D lenses.
[Rob07] Coordinated multiple views for exploratory visualization.
[SFB94] The concept of the movable filter as an interface tool.
[Shn83] The classic definition of interaction through direct manipulation.
[Shn96] Taxonomy of visualization based on data types and tasks.
[SSS02] Taxonomy of the through-the-lens metaphor.
[Tom11] A model for event-based concepts and visualization.
[WGK10] A textbook explaining foundations, techniques, and applications of visualization.
[YCB05] Models for nonlinear perspective distortion and lenses for 3D scenes.
[YKSJ07] Categorization of interaction techniques according to user intents.

Lens interaction

[ADS05] Improving gaze-based interaction with the help of a fish-eye lens.
[BLC12] Modern multi-touch techniques for interacting with stacked graphs of multivariate time-series.
[BWB06] Improved selection of small targets on multi-touch screens with dual finger interaction techniques.
[BKFD14] Analysis of transparent tangibles on tabletops and their advantages for precision.
[EWCP13] TangibleRings as intuitive tangible interfaces for nestable lenses.
[IIH*13] A research agenda for visualization on interactive surfaces.
[IU97] Tangible interaction to bridge the gap between cyberspace and physical world.
[Jac90] Eye movement-based interaction techniques.
[KAP11] FingerGlass: Interactive, bimanual touch-based lens interaction via ring objects.
[KE12] Embodied lenses: physical interaction with sheets of foil with applications to multi-dimensional data visualization.
[KPW07] Eyepoint: Gaze and keyboard interaction for magnification lenses.
[Lan00] Magnification lenses in gaze-based interaction.
[LSST11] Head-tracking for lens interactions in front of large high-resolution displays.
[LBC04] Using tangibles as handles for virtual lenses in AR.
[LGB07] Tangible lens with flexible bendable shape in AR.
[RK14] Multi-touch interaction for data visualization, physics-based manipulations.
[SSRG11] Feature tracking with lens-like handheld devices for large display walls.
[SBD12] Head-coupled perspective with tangible views.
[SSD09, SBWD13] PaperLens and tangible displays: passive and active tangible views tracked above the tabletop.
[SD13] Zones for gaze-based interaction with magnification lenses.
[SSND11] Multimodal gaze-supported interaction.
[VTS*09] Design considerations for tabletop interaction techniques.
[WKS07] Optical Magic Lenses: Using real lenses to control virtual lenses.

Biography

Christian Tominski is a researcher and lecturer at the University of Rostock, Germany. His background is in visualization with a focus on novel interaction techniques and visualization concepts for a broad spectrum of different types of data. He has developed a number of approaches of which several include interactive lens techniques. He published papers on lenses for graph visualization and lenses with application to spatio-temporal data. He also contributed to the development of tangible views for information visualization.

Stefan Gladisch is a Ph.D. student and researcher at the University of Rostock, Germany. His research concentrates on graph visualization and graph manipulation. The development of novel interaction techniques (e.g., lens techniques) utilizing interaction modalities of today's interactive surfaces is a key issue.

Ulrike Kister is a Ph.D. student and researcher at the Technische Universität Dresden, Germany. Her main research interests are in the design, development and evaluation of novel user interfaces, focusing on natural interactions and tools for graph exploration and manipulation.

Raimund Dachselt is university professor at the Technische Universität Dresden, Germany, where he heads the Interactive Media Lab Dresden. His background and research interest are natural human-computer interaction and information visualization. He published extensively about visual user interfaces and interaction techniques combining various interaction modalities and multiple displays. This includes novel applications of lenses, such as tangible magic lenses and lenses for gaze-based interaction.

Heidrun Schumann is a professor for Computer Graphics at the University of Rostock. Her research activities cover a number of topics related to information visualization, visual analytics, and rendering. Specifically, she is interested in the design of scalable visualization solutions. In this regard, the definition and display of multiple levels of granularity for numeric and graphic data is essential. She has developed various approaches related to this topic, specifically the generic concept of smart lenses, which considers lenses to be operators of in the data state reference model of visualization.