This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2018.2830759, IEEE Transactions on Visualization and Computer Graphics

Visualization of Cultural Heritage Collection Data: State of the Art and Future Challenges

Florian Windhager, Paolo Federico, Günther Schreder, Katrin Glinka, Marian Dörk, Silvia Miksch, *Member, IEEE,* and Eva Mayr

Abstract—After decades of digitization, large cultural heritage collections have emerged on the web, which contain massive stocks of content from galleries, libraries, archives, and museums. This increase in digital cultural heritage data promises new modes of analysis and increased levels of access for academic scholars and casual users alike. Going beyond the standard representations of search-centric and grid-based interfaces, a multitude of approaches has recently started to enable visual access to cultural collections, and to explore them as complex and comprehensive information spaces by the means of interactive visualizations. In contrast to conventional web interfaces, we witness a widening spectrum of innovative visualization types specially designed for rich collections from the cultural heritage sector. This new class of information visualizations gives rise to a notable diversity of interaction and representation techniques while lending currency and urgency to a discussion about principles such as serendipity, generosity, and criticality in connection with visualization design. With this survey, we review information visualization approaches to digital cultural heritage collections and reflect on the state of the art in techniques and design choices. We contextualize our survey with humanist perspectives on the field and point out opportunities for future research.

Index Terms—Information visualization, Introductory and Survey, Digital Libraries, Arts and Humanities

1 Introduction

Arguably, it is cultural expression and exchange that distinguish humans from other animals. Devising and sharing objects, ideas, and practices enrich behavioral options, facilitates problem-solving, and thus drives the evolution of human collectives [1], [2]. From physical tools and information artifacts to arts and entertainment - cultures create and collect things and pass them on across space and time. While doing so, cultures are changing, and so are the means of transmitting their assets [3]. Digitization has expanded the means for representing and transmitting cultural collections, which makes large stocks of cultural content available, in principle for everyone and everywhere. Against the background of these large data collections, new types of typically web-based interfaces are assuming a role similar to galleries, libraries, archives, and museums as the 'places', where cultural heritage (CH) can be experienced [4], [5], [6], [7].

In this report, we collect recent developments of interfaces, which leverage methods of information visualization (InfoVis) to enhance access to cultural collections in order to support their scholarly analysis and casual appreciation. The survey sheds light on this emerging field, and aims to assess the state of the art for a diverse group of readers and audiences. We assume the findings and discussions to be of relevance for InfoVis researchers and practitioners, cultural scientists and digital humanities scholars, as well as owners, curators and custodians of CH collections. The general purpose of this paper is to explore and consolidate this new field by summarizing recent achievements and by reflecting on future challenges. To do so, we will discuss the background of CH data (sec. 1) and describe our survey methodology (sec. 2). On this basis we introduce the categories of the survey (sec. 3), analyze existing visualization systems (sec. 4), and discuss the findings in relation to a range of contemporary humanities perspectives to derive directions for future research (sec. 5 and sec. 6).

1.1 Concepts of Culture

The concept of "culture" has seen a multitude of definitions [8], [9], [10]. While everyday language often uses "culture" to refer to *artful* things and emphasizes aesthetic or exceptional aspects ("the best that has been thought and known" [11]), many discourses and domains use the term in a much broader and pragmatic way. As such, culture also includes the whole portfolio of *useful* things and thoughts, including the everyday customs and practices that make up how we live as a society, "that complex whole which includes knowledge, belief, art, morals, law, custom, and any other capabilities and habits" [12]. From a functionalist perspective, CH thus comprises the whole arsenal of artful and useful assets that enable and refine collective reproduction. From a more critical perspective, CH objects and contents also always deserve a second look at their implicit functions and motivations (see sec. 5.3). Seen from such perspectives, CH objects also reveal the functions of social and cultural

- *Florian Windhager, Günther Schreder and Eva Mayr are with the Department of Knowledge and Communication Management, Danube University Krems. E-mail: firstname.lastname@donau-uni.ac.at*
- *Paolo Federico and Silvia Miksch are with the Institute of Software Technology and Interactive Systems, Vienna University of Technology. E-mail: lastname@ifs.tuwien.ac.at*
- *Katrin Glinka is with the Stiftung Preussischer Kulturbesitz. E-mail: k.glinka@smb.spk-berlin.de*
- *Marian Dörk is with the Urban Complexity Lab, University of Applied Sciences, Potsdam. E-mail: lastname@fh-potsdam.de*

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2018.2830759, IEEE Transactions on Visualization and Computer Graphics

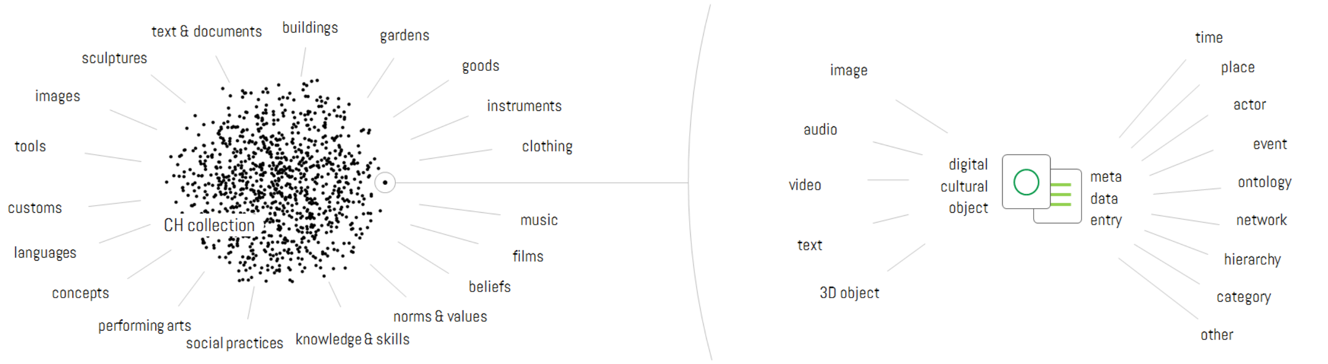


Fig. 1. Types of cultural objects and assets (left-hand side), with tangible CH at the top and intangible CH at the bottom. The right-hand side shows a closeup of the structure of CH object data, consisting of a digital cultural object (left) and related metadata entries (right).

demarcation or symbolic distinction [13], as they are also frequently (re)produced under competitive, exploitative, or hegemonic conditions and circumstances [14].

While early definitions of CH have mainly focused on tangible assets (e.g., objects, tools, artworks, or buildings), more recent conceptions also emphasize the relevance of intangible assets, such as performing arts, crafts, expressions, customs, rites, or any set of practices [15] deemed worthy of intergenerational transmission due to their *"aesthetic, historic, scientific, or social value"* [16] (see Fig. 1, left).

While cultural heritage is assembled by every collective—from prehistoric tribes and families to modern organizations and nations—its professional preservation in contemporary times is organized by institutions such as galleries, libraries, archives, and museums (often abbreviated as GLAM institutions). Besides preservation, these institutions work on their assets' documentation and availability for research, their mediation to the public, and the modernization of conservation technologies. In this context, digitization has proven to be one of the most consequential innovations. As CH institutions are gradually making their collections available online, the web is becoming a large-scale collection of cultural assets and objects itself. Bringing together the entities of countless local collections, large meta-aggregators like Europeana[1] or the Digital Public Library of America[2] are hosting millions of digital cultural objects, which can be accessed by interested visitors anytime and anywhere.

Yet to grant more generous access to these cultural riches, interface designers have to find new ways of representation beyond the common keyword search approach. They have to recreate ways and means to experience collections on large and small screens and to translate successful solutions and strategies of collection curators, custodians, cultural guides, and museum architects to these new information spaces [17], [18], [19]. To address a variety of these challenges, CH institutions and designers increasingly utilize InfoVis methods. We consider these approaches to showcase novel and noteworthy approaches to visualization design, and to be of relevance for academic, cultural and societal actors, and institutions alike.

1. Europeana: http://www.europeana.eu
2. DPLA: https://dp.la/

1.2 Relevance

From a *visualization perspective*, the relevance of CH data arises from the specific challenges they pose to the design of visualization and interaction methods. Data of CH collections are set apart from other datasets by their rich and often heterogeneous metadata, which are associated with a wide variety of object types (e.g., images, texts, artifacts, music, and films, see Fig.1). These objects often feature perceptually rich content (e.g., as realistically encoded images or object representations), and are often linked to further contextual information and historical knowledge [20]. These rich and heterogeneous data meet diverse user types [21], who pursue a variety of tasks [22]. In recent years, this complex scenario sparked a wave of InfoVis developments and approaches within and beyond the confines of academic research (see Fig.2). We consider this field of application to deserve closer and more systematic attention, and want to analyze and consolidate its technological achievements from the InfoVis research point of view.

From a wider *societal perspective*, culture is the collective expression and transmission of valuable contents and practices to ensure their continued existence. As such, we consider reflections on the technical aspects and challenges of this endeavor to have relevance from multiple perspectives:

- As a critical process of socio-epistemic reproduction, transmission of culture always requires supportive measures in terms of a culture's most advanced methods and technologies (pedagogic perspective).
- The advancement of methods seems even more essential for individuals with different cultural or educational backgrounds, whose cognitive processes are already challenged by mediating cultural and linguistic boundaries (intercultural perspective).
- Eventually, given the continuously growing collections of assets across all areas, new means for analysis, synthesis, and sensemaking with complex corpora are required (macrocognitive perspective).

Guided by these motivations, we assemble existing visualization approaches to CH data, review them from an InfoVis perspective and discuss associated challenges.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2018.2830759, IEEE Transactions on Visualization and Computer Graphics

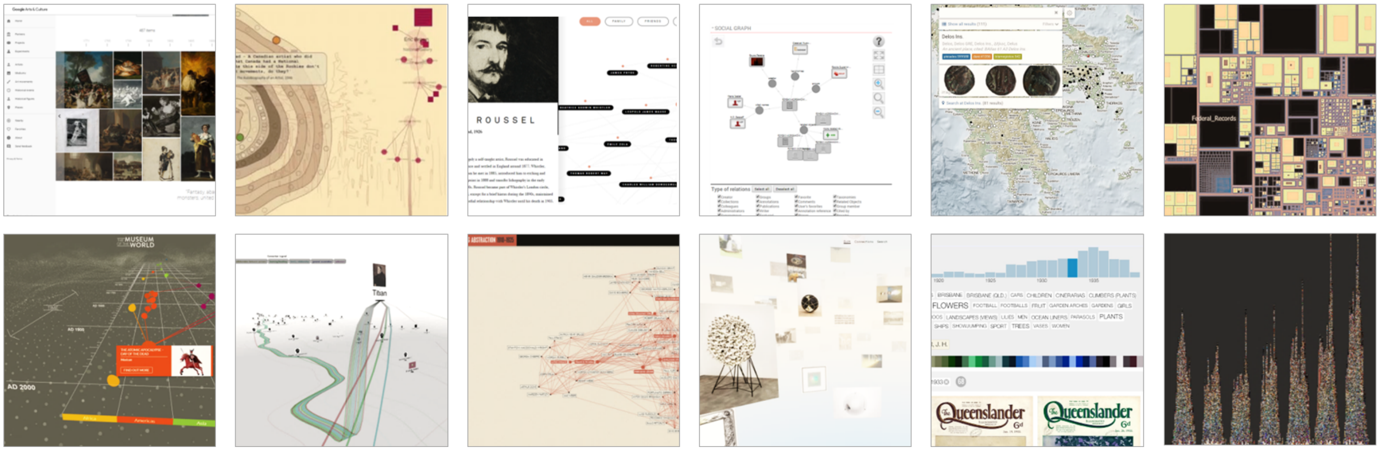


Fig. 2. A selection of InfoVis interfaces to cultural heritage data, including [23], [24], [25], [26], [27], [28] (top row), and [18], [29], [30], [31], [32], [33] (bottom row, from left to right)

2 Methodology

The survey focuses on visualizations of CH collections without restriction to a specific object type (Fig. 1, left). As such, we equally considered interfaces to collections of visual artifacts such as paintings, drawings, and sculptures, but also to text, audio, or video data that document tangible or intangible CH assets—as long as they could be represented by visual surrogates or graphical abstractions. To control this extensive search space, three criteria narrowed down our research field:

- We focused on approaches and interface designs that utilize *InfoVis techniques* for the representation of collections. Although many scientific visualization techniques for CH objects (aiming at the realistic rendering of 3D objects) exist, we included them only in the case of a hybrid use of SciVis and InfoVis methods.
- We focused on approaches with a documented application or relation to *cultural heritage data or institutions*. This criterion restricted the search space to the cultural sector, and led to the exclusion of InfoVis interfaces to, for example personal photo or music collections, or scientific text documents [34], but creates an intersection to visual text analysis in the digital humanities realm. In contrast to a recent survey in this area [160], our scope includes multiple other CH object types besides texts and predominantly analyzes visualizations based on object metadata.
- We focused on visualizations of CH object and asset collections, but did not include InfoVis systems that give their prime focus to other cultural-historical entities, like actors [35], [36] or events [37], [38].

As for the specific selection of approaches, we included InfoVis systems that have been documented by research papers or publications (see Fig.13, upper section), but also analyzed prototypical interfaces to CH collections that are publicly accessible but have not been covered by academic reflections (Fig.13, bottom section). This allowed us to include relevant work in the field that has been done without an academic focus (e.g., [29], [32]), but also to bring in tools or prototypes that are frequently used for collection visualization (e.g., [39], [40]), yet where corresponding publications, for instance, had no direct relation to CH data or institutions (e.g., [41]).

We collected approaches and interfaces through a multi-focal research process: Primary search domains included the areas of InfoVis, Visual Analytics, HCI, Digital Humanities, Digital Art History, and Museum Studies. As such, we included works from a wide range of journals (incl. *IEEE Transactions on Visualization and Computer Graphics (TVCG)*, *Information Visualization Journal (IV)*, or *Digital Humanities Quarterly (DHQ)*) and conferences (incl. *Museum and the Web (MW)*, *International Conference on Advanced Visual Interfaces (AVI)*, or *Joint Conference on Digital Libraries (JCDL)*. Starting from a core set of search terms (i.e., combinations of *data or information visualization* and *CH or GLAM data*), we sifted through related works, keywords, and research institutions, and explored incoming and outgoing citations. In case of multiple project publications, we selected only the most recent and comprehensive paper with the highest impact. Building on the results, we extended the set of keywords and iterated the search. In case of uncertainty regarding a paper's inclusion, four authors discussed the paper or interface in question, which led to the exclusion of 59 interfaces from the initial sample (e.g., [42], [43]). The final collection of InfoVis systems included 70 prototypes, with 50 prototypes associated with a research paper, and 20 prototypes investigated as web-based standalone implementations. We provide an interactive browser to explore this collection of collection visualizations (http://ieg.ifs.tuwien.ac.at/~federico/CHVis/) and ask CH and InfoVis communities to support its future extension and enrichment.

3 Categorization

For our assessment of InfoVis approaches to CH collection data we developed a classification schema with regard to the specific character of the field. It unifies top-down approaches of classification with inferential bottom-up categorizations that result from an open coding approach. The result provides a conceptual schema open for discussion and

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2018.2830759, IEEE Transactions on Visualization and Computer Graphics

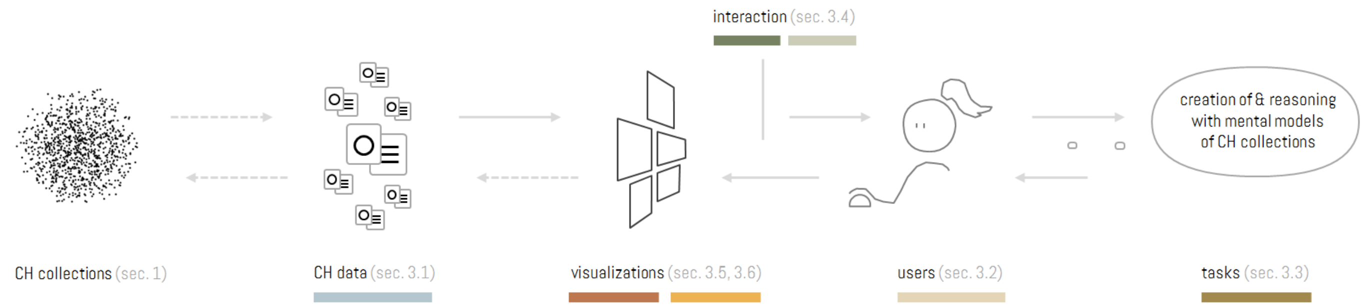


Fig. 3. Schematic lineup of a visualization system in the CH data domain with annotations and colors of the survey's main categories.

further consolidation. Where available, we elicit analytical categories from existing taxonomies in InfoVis and CH domains, which we adapt to the specifics of the target domain. As such, the first categories follow the three axes of data, users, and tasks [44], [45], with further categories pertaining to visual granularity and information activities, as well as visual encoding techniques for temporal and non-temporal aspects of collection data. In the following, we discuss each of these categories, which have been assigned to different colors for ease of differentiation (see Fig. 3).

3.1 Data

The visualization of CH collections can involve two classes of data: the data constituting the digital cultural object, and the accompanying metadata (see Fig.1, right). The metadata can describe a broad diversity of information associated with the CH objects and vary in scope, quality, and character across different collections, contexts, institutions, and domains. Therefore, to classify appearances of metadata, we need to resort to a unified and comprehensive metadata model. Among several standardization initiatives, the *Europeana Data Model* (EDM) [46] is one of the most mature efforts. The EDM reuses several existing semantic web vocabularies, such as the metadata set of the *Dublin Core Metadata Initiative* (DCMI) [47], the *Object Reuse and Exchange format* from the *Open Archives Initiative* (OAI-ORE) [48], the *Simple Knowledge Organisation System* (SKOS) [49] and the *Conceptual Reference Model* from the International Committee for Documentation of the International Council of Museums (CIDOC-CRM) [50]. Also, the *Metadata Application Profile* of the *Digital Public Library of America* (DPLA MAP) [51] is mostly built upon the EDM.

The EDM encompasses two different approaches to describe a CH object, namely an *object-centric* approach and an *event-centric* approach. The object-centric approach focuses on the static properties of the object, enabling the description of its creator, creation date, object type, and current location. However, to unlock a more comprehensive description of the object context, it might be necessary to include not only properties of the object itself, but also the properties that are associated with other object-related entities. To account for these entities, we include the following categories: **actor** (person or organization), **time**, **place**, **event**, and **ontology** (in case the visualization includes entities from knowledge organization systems).

In addition, the event-centric approach aims at building richer relational structures, such as a **network** or a **hierarchy**, by introducing contextual entities and relationships between them, including relations between objects and agents, that took part in an event at a given time at a given place. However, the two approaches are not equally distributed and established: While the object-centric approach is fully supported by most implementations and the enrichment with contextual entities partly, the event-centric approach is rarely supported. Nonetheless, relational structures can also be established in the object-centric approach by considering different types of static (i.e., non-temporal) and direct relations between objects.

In many cases, the simplest metadata assigned to an object are textual descriptions. We denote them as **text** when they are provided as free-form text, which is suitable for text visualization techniques. Conversely, when the textual description is structured as keywords or tags that can be modeled as categorical or set-typed data, we denote the textual description as **category**. Additional numerical metadata such as the number of pages of a book, the year of creation, the length of a video, or the physical dimensions of a painting are grouped under **other metadata**.

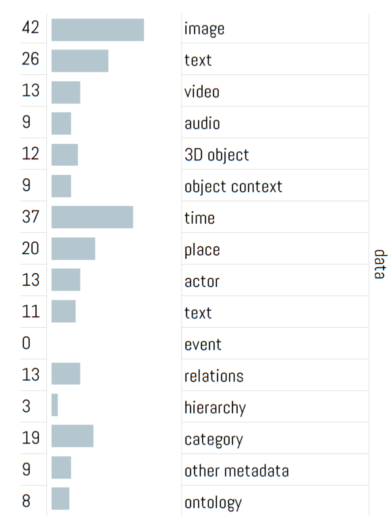


Fig. 4. Distribution of supported data types in the survey's sample.

The vast majority of approaches to visualizing CH collections are built on metadata. However, many of them also integrate a visual representation of the **content** itself. In accor-

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2018.2830759, IEEE Transactions on Visualization and Computer Graphics

dance with the EDM, we distinguish five *object types*: **image**, **audio**, **video**, **text**, and **3D object**. Because of the inherently visual nature of image objects, we observe that many of the surveyed approaches are tailored for image objects and display the images themselves. However, approaches focusing on other object types can likewise include a visual representation (as an example, books and newspapers can be visually represented by their cover images [18], [52], videos by a still [53], and 3D objects by a 2D rendering [54]). Moreover, the content of objects can be treated as data and processed or analyzed to derive additional metadata and better organize the visualized collection. Examples of applied techniques include text mining [53], [55], [56], clustering of 3D objects based on shape similarity [54], image analysis for face recognition [57], average color abstraction [52], style, genre and artist classification [58], or clustering [59]. Figure 4 shows the distribution of surveyed approaches according to these data categories.

3.2 Users

For the design of CH visualizations, the intended user is a critical factor: Users' prior knowledge, experiences, and interests will influence their expectations for and interactions with a visual interface. For this classification, we evaluate the InfoVis systems with respect to their intended users and the system's purpose.

3.2.1 Target Users

The target groups of digital CH collections are very diverse: From museum curators to humanities scholars and from highly interested enthusiasts to members of the general public - CH collections can provide useful and interesting information for all of them. Consequently, many different categorizations of users exist with respect to domain expertise, technical expertise, and motivation of use [21]. To classify and evaluate CH visualizations we distinguish two broad classes of users, namely (1) **experts** and (2) **casual users**. Experts encompass all people with a professional or scientific interest in CH data, whereas casual users are looking for personally meaningful information in everyday settings [60]. The users' domain expertise is an important factor for the design of InfoVis approaches. As research on the use of digital collections shows, domain expertise facilitates directed search in cultural databases [61], [62]. Knowledge of the content and structure of the collection enables experts to use relevant keywords for searching and filtering that yield more precise and satisfying results. Without this knowledge, it is difficult for casual users to retrieve meaningful results in search-based interfaces. They require an orientation phase before they can start engaging with the information [63]. Therefore, Whitelaw [18] suggests the development of more "generous interfaces" with rich overviews on the collection's structure and content and direct access to sample data objects within their context. Such interfaces can quickly serve casual users' curiosity, raise interest, and engage them in serendipitous exploratory browsing (see also sections 5.1 and 5.2).

Within our sample of 50 visualization systems documented by a research paper, 14 are designed for expert users, 20 for casual users, and 10 for both user groups (Fig. 5). However, six publications do not include information on their target group - a highly problematic observation, as such an InfoVis system is developed without an understanding of its future use and will probably not meet the users' needs. It is also interesting to see how an InfoVis prototype can serve two highly different user groups: Some of the prototypes designed for expert *and* casual users have distinct interfaces for each group: For example, in *Lomen* [64] all users can use different interactive views to explore the collection. Additionally, curators can create timeline-based thematic paths to tell a story about one specific topic within the collection.

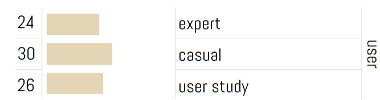


Fig. 5. Distribution of interfaces for different target groups and amount of user studies.

3.2.2 Evaluation

We also investigated whether a paper reported a **user study**, even if it was only briefly mentioned. The result was disappointing: Only 21 out of 50 papers reported a user study, and a further five mentioned one without reporting any results. Obviously, the papers that did not specify their intended user group also mostly did not conduct a user study (five out of six). Within the group of prototypes that were intended for expert use, 64% of the papers included an evaluation. In contrast, only 53% of the prototypes designated for casual users and 50% of the prototypes that were aimed at a mixed target group were evaluated. We consider these rates to be rather low, and to mirror the low level of knowledge about casual InfoVis users in general [22]. Further studies on this user group could inform and improve the design of casual InfoVis approaches in the future. For example, Hinrichs et al. [24] observed 267 interactions with *EMDialog* and found that "fancy interactions" can draw away the casual users' attention from the actual information and content. Also, evaluations with humanities researchers are needed, as their reasoning often differs from that of other practitioners using most current InfoVis systems.

3.2.3 Purpose

Additionally, we classified the purpose of the InfoVis approach: Overall, 11 InfoVis prototypes aimed for the promotion of learning or education, 19 for creating an engaging and pleasurable experience, and 20 for curating and scholarly inquiry. As expected, the purpose of the visualization correlates with the target users: Most expert approaches (93%) were intended to support inquiry and curation, whereas most casual approaches aimed at an engaging user experience (74%).

A minor amount of papers also claimed to support collaboration [54], [57], [65], [66], [67] and communication [66], [68], [69], [70]. As an early example, [54] emphasized the potential *collaboration* of different CH institutions in developing CH databases. Newer approaches furthermore argue that InfoVis opens up "opportunities for collaborations and synergies beyond academic boundaries" [65, p. 431] and that they can link the knowledge of experts and that of the

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2018.2830759, IEEE Transactions on Visualization and Computer Graphics

public. We agree that CH databases have the inherent potential to support collaborative sensemaking and knowledge exchange, but consider further transdisciplinary approaches to be necessary to tap the full potential.

The prototypes focusing on *communication* provide easy-to-use tools for curators that enable them to visualize their own data (without advanced technical knowledge) and let the public explore their collections online. Although this might also be achieved with "general tools" for creating InfoVis (like *Silk* or *Tableau*), the reviewed InfoVis tools for CH data are better tailored to the specific needs of curators. *Neatline* [70], as an example, allows curators to enrich (historical) maps with artifacts and texts for interactive exploration, whereas *Geobrowser* [39] or *Palladio* [40] foster the spatiotemporal exploration of CH data for everyone. We regard the development of such re-usable InfoVis tools as decisive in the large-scale spread of InfoVis in the CH sector.

3.3 Tasks

The categorization of *tasks* is derived from the analytical task taxonomy by Andrienko and Andrienko [71]. A task can be understood as a question involving two parts: the known part (i.e., the reference, the task constraints) and the unknown part (i.e., the target information, the data attributes to be found). The taxonomy distinguishes two types of tasks: elementary tasks, involving individual elements of the reference sets, and synoptic tasks, involving the entire reference set or its subsets, with the corresponding characteristics as a whole (i.e., a pattern or behavior).

As for **elementary tasks**, at a finer-grained level the authors [71] distinguish lookup, comparison, and relation-seeking tasks. The vast majority of approaches, which we categorized as elementary, address only lookup tasks, both direct (e.g., find all objects created at a given time in a given place, and their attributes) and indirect (e.g., given a cultural object, find when and where it was created). These approaches support users looking for specific CH objects and their attributes and aim at assisting with visual information retrieval and searching. Given the importance of interacting with individual objects in CH databases for sensemaking, it is not surprising that this is the most frequent task category. Only a few approaches also tackle relation-seeking tasks (e.g., [56], [57]).

According to Andrienko and Andrienko [71], **synoptic tasks** play an important role in exploratory data analysis. Synoptic tasks involve finding and comparing patterns, as well as seeking relations between patterns; in the context of CH, synoptic tasks can be understood as analytic activities supporting collection understanding, which shifts the traditional focus of retrieval in large collections from locating specific artifacts to gaining a comprehensive view of the collection. In our classification, among synoptic tasks, we distinguish in particular those tasks dealing with **temporal** behaviors (i.e., behaviors involving time as the reference set), because of the well-known importance of time-oriented information in CH data [72].

For Andrienko and Andrienko "the most challenging are tasks of finding significant connections between phenomena, such as cause-effect relations or structural links, and of identifying the principles of the internal organization, functioning, and development of a single phenomenon" [71, p. 48]. Indeed, the approaches we found in our survey support only elementary tasks or descriptive synoptic tasks, while further research seems to be needed to support such **connectional tasks** in the context of CH collections. Figure 6 shows an overview of the categorization by task.

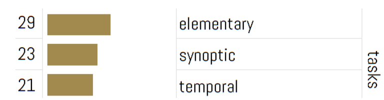


Fig. 6. Distribution of supported tasks.

3.4 Granularity and Interactivity

For digital CH collections, interface design essentially predefines how complex information spaces can be experienced. A major design decision derives from the question: which levels of object aggregation are provided? CH InfoVis systems can offer access to details of individual artifacts or overviews of entire collections - or to any other intermediate level of visual aggregation, which we refer to as *visual granularity* (Fig. 7).

3.4.1 Visual Granularity

Interaction with CH collections in a gallery or a museum mostly happens on a detail level of close-up observation or in a mode of contemplative walking from object to object. While digital collections also allow for a similar activity by the means of browsing, they also provide the option to contemplate and analyze collections from various distant perspectives [19], [72]. To conceptualize the related InfoVis design space, Greene et al. [74] introduced the distinction between previews (visual surrogates for single objects), and overviews (visual surrogates for whole collections), which we further differentiate into four types of object or collection representations:

Single object previews: To allow for a close-up contemplation, many systems provide detailed representations of objects, usually high-resolution photographs or 3D scans, but also video or audio encodings. These representations are often accompanied by textual object descriptions and the disclosure of object metadata and facets.

Multi-object previews: Above the level of singular objects, collection interfaces often aggregate previews of CH objects into multi-object arrangements, such as lists, grids, or mosaics, where thumbnails serve as object previews. As opposed to collection overviews, multi-object previews commonly represent a selection of objects and often result from searching or faceted browsing (e.g. [75], [76]).

Collection overviews utilizing discrete surrogates: At the macro level, visualization systems can provide collection overviews by using discrete abstractions for single objects such as glyphs, which keep individual objects visible and accessible for inspection while encoding metadata (e.g., temporal origin) into visual variables like position, size, color, or shape of the glyphs (cf. [33], [77]).

Collection overviews utilizing abstractions: Collection overviews can also utilize all possible types of diagrammatic representations, which abstract from discrete objects and encode collection data into any other available visualization

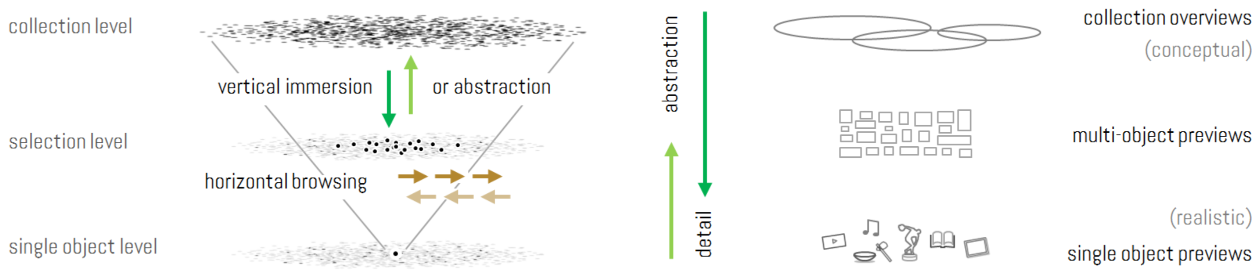


Fig. 7. Predominant information activities for CH collections, like vertical immersion or abstraction (green) and horizontal browsing (brown) (cf. [73]) and granularity levels of object collections (right), from overviews utilizing abstractions to realistically encoded object previews.

resulting in abstract geometric shapes that represent high-level patterns and structures in a collection (e.g. [28]).

In our sample of InfoVis systems, full object previews are offered by more than half of all systems, and multi-object previews are implemented by about 60%. 75% of systems offer some sort of collection overview. About half of them utilize discrete representations, and the other half use diagrammatic abstractions (Fig. 8).

3.4.2 *Supported Information Activities*

To engage with a digital collection and explore it across the outlined levels of granularity, visitors can pursue various information activities, which are predefined by an interface's interaction design. We distinguish six major types of support for different information activities [73], [78].

Object search: As a prototypical information activity, searching is geared towards finding one or more relevant objects in an otherwise irrelevant information space. At the end of a search, which equals a funnel-like task, there tends to be the single find that ideally satisfies the information need.

Overview and orientation: Collection overviews utilize conceptual abstractions or discrete object surrogates to visualize collections on a macro level. Thereby, they enable users to orient themselves according to various metadata dimensions and to visually analyze distributions, relations, patterns, or trends of entire collections on a high level of aggregation.

Vertical immersion or abstraction: Starting at a given granularity level, interfaces can support vertical movements of immersion (zoom in) or abstraction (zoom out) along the overview-detail-axis. Vertical immersion does not have to lead to the access of single objects, but can also result in the exploration of (faceted) subsets of a collection. By contrast, vertical abstraction allows the user to zoom out from the contemplation of single objects to contextualize them in their larger neighboring information space.

Accessing object details: The access to single object previews - often including access to object metadata and textual descriptions - equals the close-up contemplation of CH objects in physical exhibition spaces, and aims to engage users in a more detailed, profound, and in-depth object experience.

Horizontal exploration: As opposed to vertical immersion, which narrows down the search space, horizontal browsing or exploring includes all sorts of open-ended, lateral movements, either on the object level, or along a selected level of aggregation or abstraction. This includes browsing or "strolling" along various metadata dimensions or facets, like (same) style, artist, subject, or time [78], [79].

Curated paths: One specific horizontal functionality can be achieved by curated paths, which are generated by the interface providers (curator or author-driven, e.g. [70]) and structured by additional means of narrative information design, or by the visitors' own exploration and interaction behavior (user-driven, e.g. [76]).

Of the 70 visualization systems, about 60% offered a search functionality, 90% support overview and orientation, 65% allowed for vertical immersion or abstraction, 70% support horizontal exploration, only 20% offer curated paths, and 75% enable access to object details (Fig. 8).

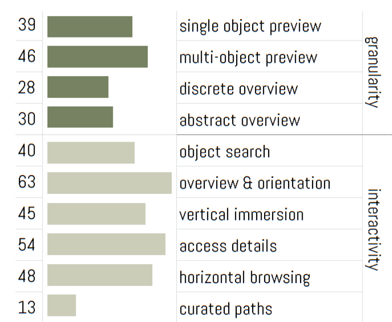


Fig. 8. The distribution of visual granularity levels (left) and supported information activities by major interaction methods (right).

3.5 Temporal Visualization Methods

CH collections are assemblages inherited from the past, experienced in the present, and preserved for the future. As such, the visual representation of *temporal aspects* is a vital design dimension. In this section we survey all InfoVis approaches with regard to their choices of how to visually encode temporal data aspects, while the next section (3.6) analyzes main methods for visualizing non-temporal data aspects. We build on existing classifications for the representation of time-oriented data [80] and distinguish six categories (Fig. 9, right).

Timelines (1D): Timelines are the simplest solution for mapping time to space in a linear, one-dimensional fashion [81]. As a method to encode the dates of origin of

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2018.2830759, IEEE Transactions on Visualization and Computer Graphics

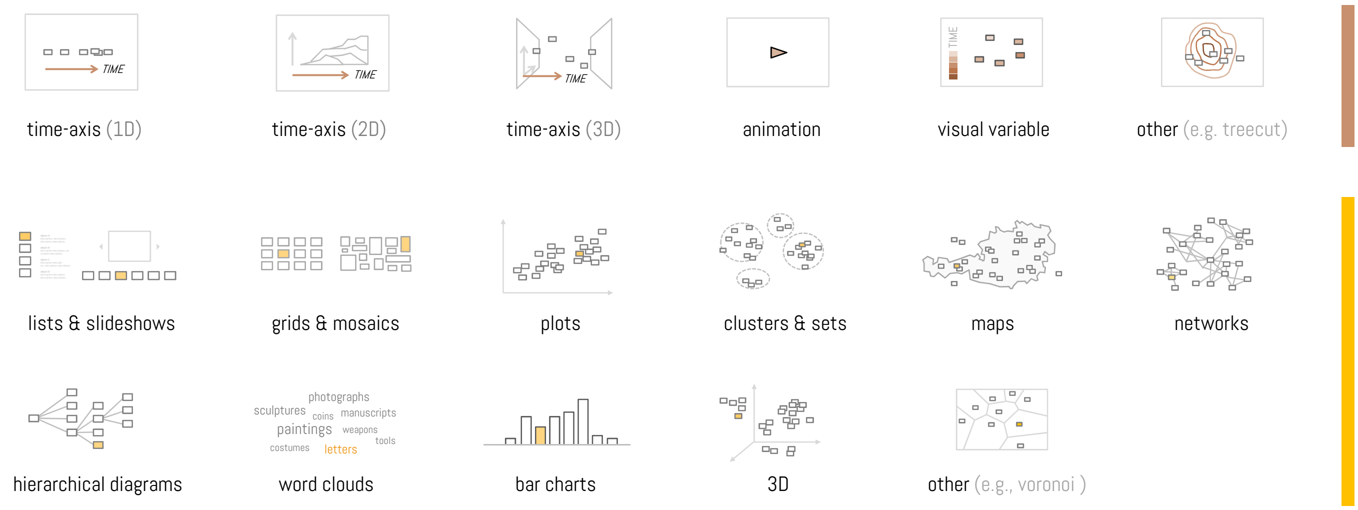


Fig. 9. Surveyed visualization methods to encode temporal data aspects (top row) and methods to visually encode non-temporal aspects of CH data collections (bottom).

collection objects, timelines commonly visualize events (e.g., creation dates of objects) as marks along a line. In a more complex arrangement, they can appear as multiple, stacked, or also faceted timelines [40], [53], [82]. Also, timelines are often utilized as "linked views" in combination with other visualizations for temporal navigation [39].

Time as one of two spatial dimensions (2D): By mapping time linearly to one of two spatial display dimensions (e.g., along the x-axis) and by utilizing the orthogonal display dimension (y-axis) for encoding another data aspect, interface designers frequently generate histograms [57], [83], line charts [84], (stacked) area charts [39], [85], time-oriented scatter plots [86], image plots [33], [67], or process visualizations [66]. These visualizations can again serve as linked views for temporal navigation and exploration, such as temporal selection, zooming, panning, and brushing.

Time as one of three spatial dimensions (3D): When interfaces make use of three-dimensional visualization techniques, temporal data aspects can also be mapped to one of three dimensions (e.g. [29], [30]. With regard to visualizations based on space-time cube representations, only conceptual designs have been documented so far [87], [88].

Animation: Using animation, the temporal change of any collection aspect is represented as a temporal change of the collection visualization on the screen. CH interfaces occasionally utilize animation to make development processes accessible as moving or morphing images, often in connection with a linked timeline. This approach offers the means for user-driven temporal navigation, selection, and further exploration [39], [40], [89].

Visual variables: By mapping time to a selected visual variable (such as color, size or texture) CH collection interfaces can transform most existing methods for non-temporal data (cf. 3.6) into time-oriented ones and add temporal information as a retinal variable (e.g., of glyphs). We found color coding to be applied mainly to collection representations on maps [40], [90], and did not identify other retinal encodings.

Other encoding techniques: Further surveyed solutions for the visual encoding of temporal data include ring charts [91], tree cut sections [24], or visualization of nodes within an ontology [92], [93]. Finally, date of creation often serves as the guiding arrangement principle for previews within lists, slideshows, grids, and mosaics.

As Figure 10 shows, only a minority of interfaces (12 out of 70) encode no temporal collection information whatsoever. Among the majority of interfaces that do, the most prominent methods map time to a spatial dimension, with 30% of all interfaces using one-dimensional timelines, and close to 50% using one out of two spatial dimensions. 3D encoding has been used only by two interfaces, and encoding to visual variables has been applied by three. Twenty percent of all interfaces utilized other options for the visual encoding of time.

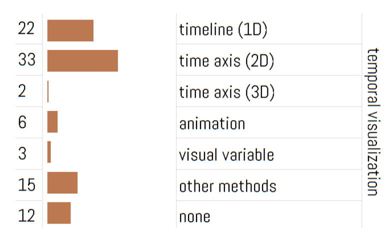


Fig. 10. The distribution of methods for the visual encoding of temporal (time-oriented, longitudinal) CH collection data aspects.

3.6 Non-temporal Visualization Methods

Finally, we analyze all systems for visualizations of other than temporal data aspects, including *spatial, relational, distributional, categorical or cross-sectional* collection aspects (Fig. 9, left).

Lists & slideshows: Horizontal slideshows or vertical lists arrange object collections in a linear sequence. While we did not consider such widely used multi-object previews (including grids & mosaics) to count as InfoVis techniques in the narrower sense, some of these arrangements encode

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2018.2830759, IEEE Transactions on Visualization and Computer Graphics

additional data dimensions (e.g., temporal origin, dominant color or item popularity) into the previews' positions, and allow for user-driven re-arrangement, which makes them a relevant arrangement technique at the InfoVis periphery.

Grids & mosaics: Using "line breaks", linear arrangements turn into grids and mosaics, which arrange multi-object previews in multiple rows that raise the item-screen ratio (e.g. [23], [77]). Furthermore, grids and mosaics can be dynamized, so that tiles represent whole object categories or subcollections and change their content over time. Thus, also passive contemplation without clicking and scrolling is enabled [18].

Plots: Dissolving the contiguous arrangements of grids and mosaics, plots assign the two-dimensional (x and y) positions of previews or glyphs according to selected metadata dimensions in a coordinate system. Examples are image plots [33] and scatter plots [68], [94], [95], which utilize glyphs or point-like abstractions instead of object previews. As a result, distributions (clusters, outliers, gaps) appear that allow for the analysis of collection patterns or trends.

Clusters & sets: To unveil possible inter-object similarities implicit in multiple dimensions of collection data, dimensionality reduction procedures can be applied. This includes principal component analysis (PCA), multidimensional scaling (MDS) and t-distributed Stochastic Neighbor Embedding (t-SNE). With such techniques, CH collection data can then be visualized as image or glyph clusters [33], [83], [96]. If object similarities are explicitly defined (whether as group, class, or categorical object attributes), these object clusters can be visualized by set visualizations [32], [97].

Maps: As geographic origin is one of the most frequently documented metadata dimensions of cultural objects and artifacts, maps accordingly serve as a prominent visualization method to show the spatial distribution of artifacts' origins [39], [40], [90]. Likewise, CH objects' provenance histories (i.e., their spatio-temporal trajectories) can be visualized in a geographic context [89].

Networks: As for relational aspects of collection data (e.g., influences, references, inter-artifact relations, linked-data relations), network diagrams allow users to explore the proximities and distances of artifacts or cultural actors in relational or topological spaces [26], [40], [72]. While force-directed layouts often interrelate CH objects and related entities [76], graphs are also implemented to visualize relations between object metadata [56] or within metadata ontologies [91].

Hierarchical diagrams & maps: Given the different possible classifications of cultural artifacts, hierarchical diagrams such as treemaps are one solution to offer insights into hierarchically structured constellations of object or collection metadata [28], [97].

Word clouds: Word or tag clouds [65], [98] are a prominent method of visualization and verbalization to represent metadata aspects of a collection. Tags or keywords can be derived either from existing object classification, mined from object titles and related textual descriptions, or generated through crowdsourcing or computer-vision methods.

Bar charts serve as another prominent visualization method for CH collection data [75], including their use as histograms to encode the temporal distribution of a collection's historical provenance (e.g. [82], [83]).

3D: Going beyond the two dimensions of flat InfoVis design, some interfaces also use a third dimension to encode CH collection data [30], [99]. This includes hybrid systems that merge the visualization of abstract data aspects as (or within) virtual spatial environments [32], [54], [92], [98].

Other encoding techniques: With regard to the many possible dimensions of CH collection data, a whole range of further InfoVis techniques provide insights into non-temporal patterns and distributions, including (stacked) area charts [85], ring charts [72], Voronoi maps [100], pie charts [68], Kohonen maps [101], or line charts [102].

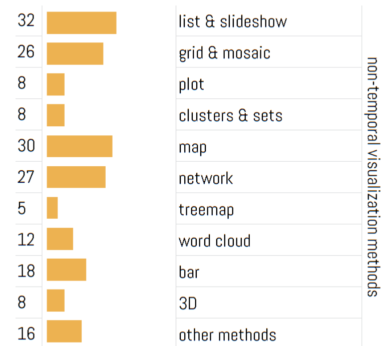


Fig. 11. The distribution of visualization methods for non-temporal (spatial, structural, relational, distributional, or cross-sectional) CH collection data aspects.

Overall, more than half of all interfaces (55%) featured at least one type of a multi-object arrangement, such as lists, grids or mosaics. As for other visualization methods, geographic maps (30) and networks (27) are the most frequently utilized techniques. After that, bar charts (18), word clouds (12), cluster visualizations (8) feature prominently, followed by 3D visualizations, plots, and treemaps (Fig. 11).

4 Survey and Analysis of Interfaces

Overall, we analyzed 70 InfoVis interfaces across six main categories and 48 subcategories (Fig. 13). For all 50 prototypes documented by papers or similar publications, we were able to apply all categories and do our assessment across the full spectrum. For 20 InfoVis prototypes without a published documentation, we refrained from assessing the underlying data types, as well as intended users and supported tasks due to too large a margin of interpretative uncertainty. While the overview table discloses the structural profiles of interfaces in the general design space (rows), it also sheds light on the prominence of individual design elements and features (columns). Furthermore this table offers a documentation of design decisions for developers, who can look up the design solutions of existing visualization prototypes that deal with the same types of data. In addition to these basic functions, we highlight additional findings.

4.1 Interest in CH Visualization

An analysis of the publications by year (Fig. 12) reveals that the field of CH visualization is quite young: The first publication stems from 2004 [103] and an increased interest can be observed from 2010 onward. Since then, the publication statistics show an upward trend (with fluctuations). This

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2018.2830759, IEEE Transactions on Visualization and Computer Graphics

trend mirrors the development of the major repositories for CH data in the last decade: The Europeana project started in 2007, and the DPLA in 2010. Both currently offer open access to huge digital CH collections, raising questions on potential use cases for these data, but also enabling their re-use in research. Also on a local scale, an increasing number of collecting institutions have invested time and money into the digitization of their collections.

This rapid growth in CH data motivated the use of InfoVis technologies, which help to make sense of massive data collections, and offer effective means to interact with these data. The development also parallels the rise of the Digital Humanities as a new research field in its own right. Consequently, with the continuous increase in available data and evolving interdisciplinary research expertise in the relevant fields, interest in applying InfoVis approaches to CH collection data grew over time and will likely continue to do so.

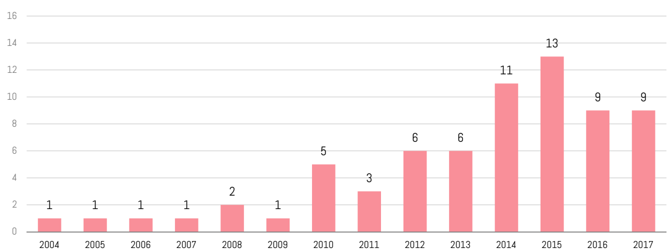


Fig. 12. The temporal development of CH InfoVis publications.

4.2 Observed Impact

What are the most important publications on CH visualization? To evaluate the scientific impact of the surveyed publications, we conducted a citation analysis using Google Scholar in June 2017. Six publications could not be included in this analysis as two of them were published too recently to be listed, and four were published on the *Museums & the Web* website which is not indexed in Google Scholar. From the remaining papers, most received only little attention based on the Google Scholar citation (Fig. 14). The 10 papers with the highest impact ranged from 22 to 110 citations. Nearly all early publications that were published before 2010 are found in this list (five of six), probably partly due to their extended time for reception, but also due to their pioneering status.

To understand, what distinguishes a low- from a high-impact paper, we considered the three most cited papers more closely. It becomes clear that they go well beyond the scope of describing singular InfoVis systems, but rather discuss more general concepts, which obviously proved to be useful for other researchers. The most often cited paper is by Thudt et al. on the Bohemian Bookshelf [52], in which the authors build on the theory of serendipity and delineate general design requirements for InfoVis in support of serendipity. Similarly, the second most cited paper by Hinrichs et al. [24] conducted a large user study on the use of EMDialog in an exhibition context and reported several lessons learned for the design of InfoVis. The third most cited paper by Shen et al. [93] formalizes the processes of searching and browsing and discusses how they are linked and can be integrated into the InfoVis of the ETANA digital library. These three high-impact publications illustrate how the engagement with CH data encourages visualization researchers to not only work across disciplines, but also to propose new ways of thinking about visual representation and interaction.

4.3 Casual vs. Expert Use

The design of an InfoVis system strongly depends on the intended user group. As digital CH collections serve mainly two different target groups, we expected differences between interfaces for expert and casual users. However, these differences were not as fundamental as expected.

We already reported that the documented purpose of the InfoVis interface changes with the targeted user group (cf. section 3.2.3) in that expert interfaces are intended for inquiry and curation whereas interfaces for casual users are geared towards an engaging experience. Consequently, also the supported exploration activities differ: providing an overview is important in all interfaces for all user groups and represents one of the fundamental benefits of InfoVis. In addition to this, browsing techniques were implemented more frequently for casual users, while for experts the search function was more prevalent. This observation is in line with existing research showing that experts are more skilled in searching CH databases than casual users [61], [124] and that casual users require alternative modes of access to pursue exploratory search [62].

Moreover, we observe a difference between user groups in terms of object types: Interfaces for casual users focus more on image objects than approaches for professional users, and often also display a thumbnail of the image itself; we can reasonably suppose that many interfaces for casual users are designed to engage them in browsing object reproductions rather than support exploratory analysis of object metadata.

Similarly, we observe a difference in terms of supported analytic tasks. In particular, approaches supporting elementary tasks are slightly more prevalent (60%) among those designed specifically for casual users; conversely, approaches supporting synoptic tasks are more prevalent (73%) among those designed specifically for experts. Approaches focusing on both user groups support both task types nearly equally.

With regard to multiple views, one could expect that interfaces for casual users should be simpler and provide fewer ways of visualizing data. However, no differences exist in the number of implemented visualization methods. But the kinds of visualization techniques differ: Expert interfaces use fewer lists, grids, and tag clouds than casual interfaces. As list and grid visualizations are fundamental ways for browsing a visual collection, this matches the results observed for the exploration activities that casual users more often browse than search.

4.4 Multiple Views

From a visual analytics perspective, the complexity of CH data implies that every possible encoding method can capture only so much of a collection's composition

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2018.2830759, IEEE Transactions on Visualization and Computer Graphics

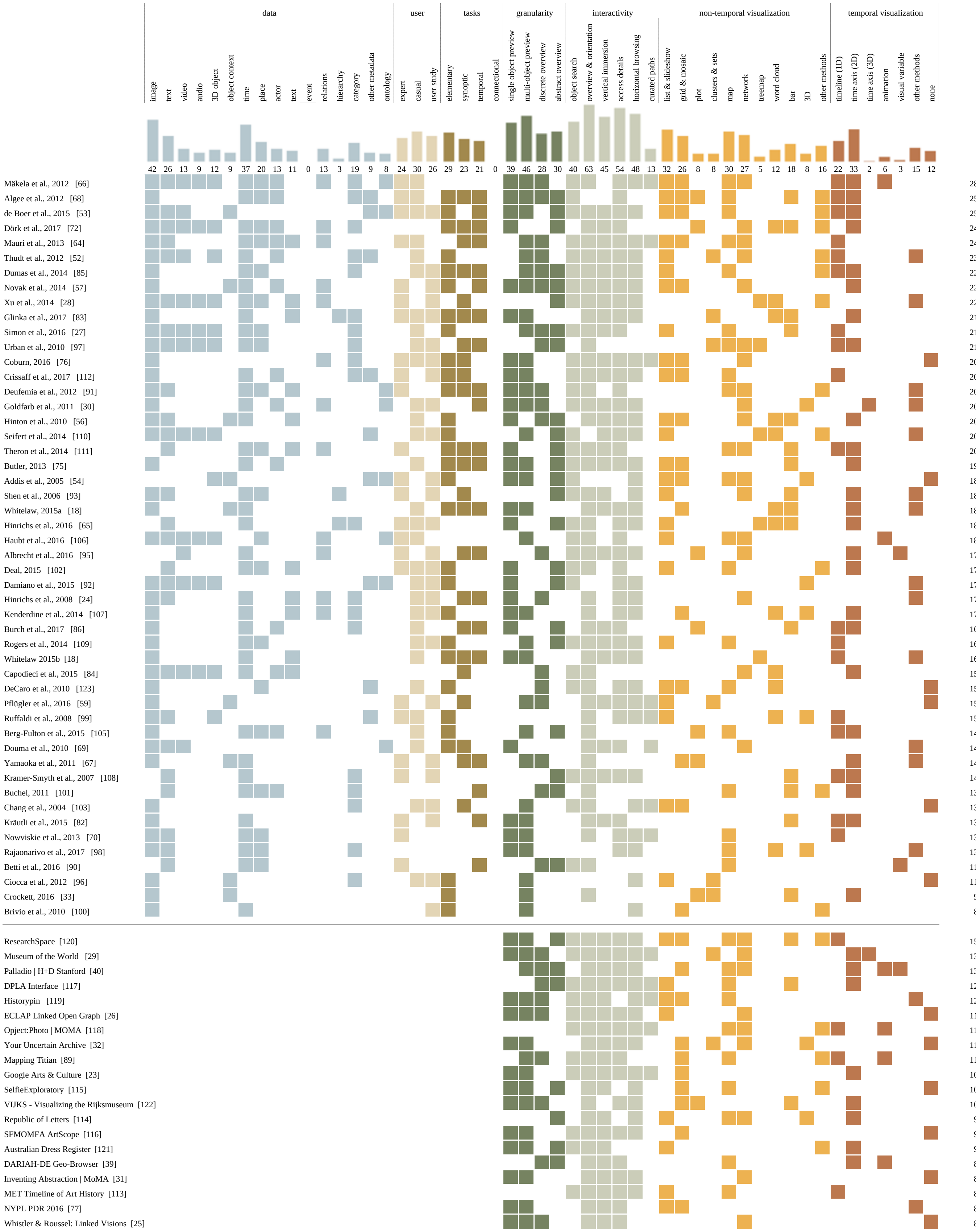
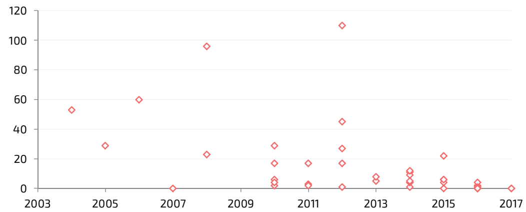


Fig. 13. Design space and categorial distribution of all surveyed InfoVis interfaces to CH collections, with paper-based prototypes at the top, and publicly accessible prototypes without associated publication at the bottom. Ranking according to number of design features.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2018.2830759, IEEE Transactions on Visualization and Computer Graphics



citations	author (year)	title
110	Thudt et al. (2012)	The Bohemian Bookshelf: Supporting Serendipitous Book Discoveries through Information Visualization
96	Hinrichs et al. (2008)	EMDialog: Bringing Information Visualization into the Museum
60	Shen et al. (2006)	Exploring Digital Libraries: Integrating Browsing, Searching, and Visualization
53	Chang et al. (2004)	Collection Understanding
45	Mäkelä et al. (2012)	How to Deal with Massively Heterogeneous Cultural Heritage Data – Lessons Learned in CultureSampo
29	Addis et al. (2005)	New Ways to Search, Navigate and Use Multimedia Museum Collections over the Web
29	Brivio et al. (2010)	Browsing Large Image Datasets through Voronoi Diagrams
27	Ciocca et al. (2012)	Browsing Museum Image Collections on a Multi-touch Table
23	Ruffaldi et al. (2008)	Design of Information Landscapes for Cultural Heritage Content
22	Whitelaw (2015)	Generous Interfaces for Digital Cultural Collections

Fig. 14. The number of citations per paper and top 10 publications.

or structure. According to the design rationale “one view is not enough” [72] the survey shows that the use of *multiple non-temporal perspectives* (either as multiple-choice or multiple coordinated view systems) is a widely used technique to combine the strengths of different views—and to counterbalance possible analytical reductions of a singular technique. About 80% of all interfaces utilize more than one non-temporal visualization method. On average, 2.63 (SD=1.18) different non-temporal encoding techniques were used, ranging from 1 to 6 [68]. The most frequently implemented non-temporal encoding techniques are also most often combined: lists, grids, maps, and networks.

The temporal dimension in CH data was visually encoded by 81% of the CH InfoVis interfaces. According to Kerracher et al. [125], offering multiple views “to maximise insight, balance the strengths and weaknesses of individual views, and avoid misinterpretation” is also highly relevant for *temporal analysis*. Visualization systems increasingly combine different visual approaches to temporal aspects to allow the user to select and switch between the most appropriate representations for the data and task at hand [125]. This trend seems to also manifest in CH collection visualization: One out of three systems (31%) implemented multiple encoding techniques for temporal data aspects (e.g., [40], [89]). The implementation rates of 1.16 (SD=0.76) different temporal encoding methods per system (ranging from 0 to 3 [66] [40]) are still significantly lower than for non-temporal visualizations. Given the relevance of the historical data dimension for cultural sciences and humanities scholars, we expect these rates to grow. With regard to the combination of temporal and non-temporal encoding methods, we found that 1D timelines are most often implemented together with lists, maps, and networks. 2D-time axes are often combined with lists, grids, maps, and networks. The methods of animation and color coding are mostly combined with maps and networks.

As one remarkable result, we found practically no hybrid systems integrating InfoVis techniques with 3D rendering techniques (e.g., of real or virtual museums), even though such combinations could provide multiple insights into the connections between abstract and concrete arrangements [126]. We want to mark this as a particularly interesting unexplored possibility and emphasize its future potential (also for VR/AR guides), so that sensemaking in physical and digital information spaces can mutually amplify their potential (see sec. 5.5).

4.5 Intangible Heritage

As the distribution of data types in the survey shows (Fig. 13, blue column), there is a remarkable shortage of interfaces enabling access to *intangible* objects or practices, such as music, film, performing arts, or linguistic entities (e.g., narratives, folk tales, or poems). One hypothesis to explain this absence of interfaces to intangible cultural heritage is that texts are mostly found in specific-purpose libraries. Moving images or music on the other hand might be either stored in similarly specific collections, or shared and transacted mostly on commercial and private platforms. Regardless of its origins, we consider this large structural blind spot to delineate one of the most promising areas for future developments. As countless domains of the humanities, arts, or cultural sciences have assembled itemized knowledge and data collections about their focused intangible phenomena, practices and objects of study (Fig.1, left-hand side), most of the surveyed InfoVis approaches are also applicable to their data.

As such, intangible CH data collections (e.g. as curated by the UNESCO [127]), which include various forms of knowledge and practices, oral traditions and expressions, performing arts, social practices, rites, customs, rituals and traditional craftsmanships, could be visually explored and presented by the modern means of all the available InfoVis methods outlined so far. Likewise, humanities disciplines (such as ethnography, sociology, history, or cultural anthropology) document and collect phrases, folk songs, poems, recipes, concepts, ideas, habits, customs and practices. We assume that most of these itemized collections can also be represented on the basis of associated metadata, and that therefore related research and teaching initiatives could also benefit from most the visualization methods and techniques enlisted above.

5 Discussion

As evidenced by the survey so far, recent developments in the area of CH representation have motivated a multitude of visualization approaches, which begin to form an interconnected field of study with its own questions and challenges. These novel challenges have been answered by a discussion about newly required design principles and strategies. In the following, we discuss a selection of these perspectives, which emerge from multiple strands of discourse between digital humanities, cultural sciences, and information visualization. They are in part a response to early InfoVis developments, and we consider them to be valuable voices shedding light on possible future demands for advanced visualization design in the CH data realm.

5.1 Serendipity

The concept of serendipity originates mainly from discourses in library and information sciences. In its literal meaning, serendipity describes "the faculty or phenomenon of finding valuable or agreeable things not sought for" [128]. Although coincidence, unexpectedness, and accidental discovery are also associated with the term, in particular in the sense of "unexpected" or "accidental" scientific discoveries [129], we want to emphasize the potential to deliberately incite and encourage serendipitous information retrieval. While it is not possible to directly control serendipity, it nonetheless can be influenced [130]. It could be argued that the well-structured and curated presentation of collections in museums or libraries allow for strolling along a multitude of paths through the *information space*, and encourage serendipitous encounters. This creates the effect that visitors will likely come into contact with information (books, exhibits, objects) "that are of interest to them but that they were unaware of prior to visiting" [131].

Options for operationalization: In the context of digital CH collections and interfaces, the question of how to support serendipity is not easily answered [130]. One approach is seen in emulating the serendipitous information space of a library or museum in digital CH interfaces [132]. Others rely on search interfaces but offer a slightly more serendipitous access in the sense that related or similar objects to the one searched for are also recommended based on existing object taxonomies or user-generated tags [131], by providing hypertext links between related entities [130], or by suggesting items that are otherwise related to the viewed entities [133].

The specific potential of InfoVis for encouraging serendipitous information retrieval was first illustrated by the Bohemian Bookshelf [52], which applies several serendipity-focused design principles, such as multiple visual access points, highlighting adjacencies, enticing curiosity, and supporting playful exploration. Another example is the Past Paths project [76], [134], where the scrolling speed controls the display of items. Slow speed shows only related items, whereas higher speed highlights seemingly random new topics. To support orientation, the users can store items of interest and explore their past paths in visualizations that highlight relations between the accessed items [134].

Being quite an elusive term and concept, there is no established recipe for designing serendipitous collection interfaces or InfoVis environments. However, the principles of serendipitous encounters, including, for example, the value of unexpected discoveries, the feeling of surprise, the challenging of familial interactions, and the enabling of unpredictable results, might offer a way to evoke corresponding experiences [135]. Still, thorough user studies have not yet been conducted that would help us to fully understand how specific design decisions influence users' perception of serendipity. Nonetheless, the intention to increase the likelihood of serendipitous encounters within a digital CH interface is likely to help create more open, more diverse, and possibly more engaging user experiences.

5.2 Generosity

Relatedly, the notion of "generous interfaces" [18], [75] revolves around the question of how digitized CH can be made accessible in a way that is also able to "reveal the scale and complexity of digital heritage collections" [18]. At its core, it is characterized by a clear contrast to what still is a default starting point in many digital interfaces: the search slot. The generous approach to collection interfaces defines five principles: i) show first, don't ask; ii) provide rich overviews; iii) provide samples; iv) provide context; and v) share high quality primary content [75]. It aims to provide rich and navigable representations that encourage exploration and browsing [18], while overviews establish context and maintain orientation during access to details at multiple scales.

Options for operationalization: The principle of generosity explicitly confirms well-established design principles of InfoVis, which emphasize the importance of overview, orientation, and details on demand [136]. It also promotes the utilization of multiple (over)views (see sec. 4.4), to form complementary composites that reveal different aspects of a collection—what Drucker terms "parallax" [137]. It also promotes more playful extensions of information seeking towards less goal-oriented information activities, such as satisfying curiosity, enjoying aesthetics, and avoiding boredom. Rather than the functional satisfaction of an information need, generosity emphasizes process, pleasure, and thoughtful engagement [18], requirements as they have been documented for casual users [60], information flaneurs [73], and humanities-based approaches to interface design [138].

In this sense, the concept of generosity - together with concepts of criticality (see section 5.3) - can arguably help to overcome all overly narrow task- and deficiency-driven approaches to interface design that are grounded in a simplistic user-as-consumer- and problem-solver-model [137]. From this perspective, the first half of this survey's categorization schema (centered around data, users, and tasks) may appear to be a questionable choice for analyzing interfaces for "humanities-based" experiences. However, by encouraging the elicitation of humanities scholars' tasks and requirements, we consider their needs as inputs to be taken seriously for participatory system development. Only sustained and systematic collaboration might enable more reliable collections of humanities-specific requirements and conventions. We see this as a necessary step towards the design of methodically and epistemologically less "trojan horse" [139] technologies, as well as their ecologically valid evaluations.

Also, the principle of generosity goes beyond mere design implications and also includes the call for open data, open source, and open access. Last but not least, generous design aims for the deliberate generation of novel questions and critical inquiries, such as going below the surface of given assumptions (sec. 5.3) and looking beyond all local confines (sec. 5.7), rather than claiming to exhaustively show "what is" [18].

5.3 Criticality

With the principle of criticality we refer to reflections and design strategies, that can help to meet specific epistemic

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2018.2830759, IEEE Transactions on Visualization and Computer Graphics

standards in various humanities, arts, and CH communities. Some of these standards mainly aim to prevent unverified or realistically naive renderings of CH topics, data, and subject matters, and instead support interpretive accounts and critical analyses of authoritative representations and their assumptions [139]. In this context, visualizations and interfaces can and should not claim the status of being inevitable technical solutions. To the contrary, they have to be addressed as cultural artifacts themselves, which require thorough reflection, critique, and appropriation [73], [140]. For this purpose, we see largely two options: encouraging the level of critical self-reflection on the side of visualization designers, and at the same time, raising the critical (data and visualization) literacy skills on the users' side.

Options for operationalization: To raise the criticality of CH visualizations and interfaces, we promote design principles and guidelines that promote disclosure (making data and design choices transparent), plurality (offering multiple views and perspectives), contingency (acknowledging the open-ended nature of user experience), and empowerment (fostering user's self-activation and engagement) [141]. These principles can help to question interfaces, and gain a second look at their seemingly realistic demeanor [138]. Even more so, they help to have a critical look at the data and design choices, and to revise or refute (parts of) visual representations, including their rhetorical devices [142]. If these rejections can be documented together with alternative design suggestions, a multimodal version of "critical theoretical" discourse might ensue, drawing on texts and visual representations alike.

We see a specific relevance of such a critical discourse when it comes to CH collections and data, which are often heterogeneously interpreted in pluralistic humanities discourses, depend on the disclosure of sources, are intertwined into subjective histories, and relate to multiple questions of provenance, methods, and disciplinary traditions. We also see a need to include CH institutions in critical reflections, which influence collection interpretation by their ways of cultural mediation, including exhibitions, catalogues, and their overall framing of collections. Since at least the 1990s [143], critical discourses in the context of institutional critique, postcolonial studies or feminist theory have vigorously been advocating for a more nuanced, self-reflective practice of collecting and exhibiting. This has moved many institutions—in the light of public and academic scrutiny—to openly reflect their history, their entanglement in hegemonial structures and power relations, and also acknowledge the need to address these issues when engaging in a dialogue with the public. In simple standard interfaces to CH data, these discourses cannot be equally represented. Yet the understanding of CH collections as dynamic entities that can be formed, re-arranged, contextualized, and annotated through innovative forms of participation can be specifically supported [144]. Equally, InfoVis and interface design holds the potential to allow for multiple, uncertain, and sometimes even conflicting perspectives and narratives to surface (cf. sec. 5.6 and sec. 5.4), while keeping the physical structure and "authoritarian" metadata of a collection intact.

All of these options to foster a critical utilization of visualization technologies eventually depend on the skills and intentions of users and visitors to apply them. When developing visualizations and interfaces in a CH context, the intended users' expected skills should be thoroughly reflected, as well as their prior knowledge and assumptions. Only these sorts of reflections—together with corresponding onboarding techniques and educational initiatives—can lead to the establishment of critical data and visualization literacy. As a result, a new form of "source criticism" for representations in digital environments could emerge, which is duly needed not only in the humanities.

5.4 User Guidance and Narration

Design strategies of user guidance and narration enrich the standard mode of individual and user-driven visualization reception. User guidance by *recommendation* provides suggestions for the extension and continuation of a certain viewing experience—often by clustering related material around objects or areas of focus. Existing metadata of CH collections often support faceted browsing and recommendations corresponding to data dimensions (e.g., similar style, artist, subject, or any other category). In addition to the existing records, algorithmically derived metadata and recommendations can be used when developing a visualization [133], [144]. Machine learning in combination with computer vision has shown great potential for extracting visual features that allow us to go beyond the manual annotation of large collections [58] and thus contain the potential to critical intervention [144]. Also, similarity-based layouts can be used to create visual arrangements that are based both on the objects' metadata and on the algorithmically derived similarity of the images [145]. Users can also be invited to curate and recommend their own collections and assemblies, and share as guidance with the public—and even inspire others to creatively engage with the material in artistic practice and design [146].

User guidance can also be implemented as a form of *narrative*, by offering suggested paths or sequences of sensemaking. The design principle of storytelling has been intensely discussed in the InfoVis community [147], [148], [149], as it brings back author-driven techniques of sensemaking into a field originally focused on user-driven analysis. For the traditional presentation of CH collections, narrative arrangements are quite usual. Museums frequently rely on curatorial expertise when they make content available. One of the purposes of curation can be regarded as "narrating the collection", i.e., telling a story by selecting and presenting objects in a purposeful manner, accompanying them with additional information, and even guiding visitors through and between exhibits. Commonly, visual interfaces to digital CH collections disrupt the pattern of search-centric interfaces and provide more generous tableaus of objects and overviews, including the means for individual vertical exploration (zooming, immersing, details on demand [136]), and for horizontal browsing and strolling [73], [78]. Going beyond these user-driven movements, narrative design offers curator-driven pathways that extend the information seeking mantra [136] with the option to *"enjoy sequential guidance on demand"*. While narrative visualizations can be completely author-driven, most examples find ways to balance author- and user-driven modes of experience [147]. As

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2018.2830759, IEEE Transactions on Visualization and Computer Graphics

such, interface designers can allow users to drive their visits to collections individually, but also to lean back, and follow a narrator's suggestions and connections.

Options for operationalization: In the context of visual interfaces to CH collections, narrative guidance can be implemented, for example, as animated movements across a map, which may include different textual and visual source materials [70], [89]. Narration can also follow a curator's storyboard along various spatial (i.e., linear or axial) encodings of time as with timelines, flowcharts, or tree diagrams [150], or also in 3D space [151]. The guidance can be author-driven (e.g., by curators [64]), user-driven [23], [29], or even created by users with their own CH data [70]. Users can store their individual path through a collection and share it with others [76], [134], which allows the publication of alternative and critical narratives in addition to the "authoritative" narrations created by commissioned curators. With regard to balanced approaches we found a largely untapped potential to interweave storylines into visual tableaus (see also the options of martini glass structures, drill-down stories, and interactive slideshows [147]), and thus to deliberately synthesize the author- and user-driven modes of experience in the context of CH collections and data.

5.5 Remote Access vs. Being There

Differences between *on-site* experiences of CH collections and modes of *remote access* to CH collection data have already been discussed with regards to a common lack of narrative guidance in traditional CH interfaces (see above). On a more general level, the idea of bridging the gap between collection visualizations on screen and their appearances in physical settings refers to a unique challenge for visualization design. Most papers in this review discuss web-based InfoVis prototypes. A minority used and evaluated mobile systems [109], which could be used both remotely or in-situ. In their study, Rogers et al. [109] observed different patterns of use in virtual and physical museum environments, in particular, the entry point depended on the interaction taking place remotely or in-situ. Also, overviews linked with individual artifacts tended to promote exploration in the remote setting, while in-situ it was the physical artifacts driving explorations. This finding alone makes it obvious that InfoVis systems developed primarily for remote use will not necessarily serve the information needs (or maybe rather expectations) of museum visitors.

Options for operationalization: We consider the in-situ use of exploratory interfaces and collection visualizations in real CH exhibition settings to be a largely unexplored area of application. For the interconnection of on-screen and off-screen experiences at exhibition sites, multiple constellations exist, from the in-situ use of public screens [152], [153] and mobile applications [109] to immersive installations [107], to a whole spectrum of virtual, augmented or mixed reality solutions [154], [155]. These solutions can focus on the well-known requirements (from overview and orientation to providing details on demand) for the visible parts of a collection or also go beyond. Given the fact that only a small percentage of an institution's collection is usually on view in exhibitions or visible storage, visualizations can bring information about off-display objects (or even about a whole range of contextual knowledge, see sec. 5.7), back into a museum's hall, to enhance the overall visitor experience.

5.6 Facets of Uncertainty

Within visualization research, the question of how to deal with uncertain data already belongs to one of the standard exercises of the field [156]. When dealing with CH data, the question of uncertainty is often discussed in the context of digital reconstruction of CH sites and 3D visualization [157]. When it comes to InfoVis of CH collections, we see a lack of discussion on the same level. One of the most prevailing but also challenging metadata entries in CH collections is "date" (sec. 3.5)—as it poses not only challenges of the historically exact dating or age determination, but also in regards to different concepts of time and the question of what date should be recorded and represented. Is it the date or period of production, of public display in its original setting, or of a sale or resale of a given object—or even a combination of several dates [158]?

Options for operationalization: Kräutli and Boyd Davis [158] suggest not to render these uncertainties invisible by creating visualizations that represent time as exact, but instead integrate visual renderings of probabilistic time descriptions. This would relate to the humanities' convention to do the same on a textual basis. However, while general visualization research has addressed the visual encoding of temporal uncertainty [159], InfoVis for CH also needs to take on the challenge of visually representing interpretation and ambiguity on a more general level. Drucker argues that the visual representation of ambiguity and uncertainty also might require a shift away from standard metrics to metrics that express interpretation [138].

For the sources that introduce uncertainty into the age determination of artifacts, Kräutli and Boyd Davis have assembled a whole list, including the "inherent imprecision of the world" and the "interpretation by curators" [158]. We consider this list of factors to influence almost all metadata dimensions (see sec. 3.1), including places, actors, relations, and even more so all available ascriptions of meaning. The acknowledgment of imprecision and interpretative openness that is present in textual sources in the humanities have hardly been acknowledged in the design of CH interfaces and visualizations. As these factors also tend to be rendered invisible in visual interfaces, there is a multitude of challenges for representing uncertainty in various data dimensions for future visualization approaches.

5.7 Contextualization

Emerging standards for *linked data* (see the "event-centric" approaches to CH data in sec. 3.1) provide new options of enhancing, contextualizing, linking, and reframing CH objects and collection data [161]. Linked data is a way of publishing structured data that allows metadata of different local databases to be connected and enriched, "so that different representations of the same content can be identified, and links between related resources can be made" [20]. As such it introduces new potentials for the enhancement of collection data and might eventually support the overall processes of sensemaking by connecting CH data silos and allowing for cross-domain representations and reasoning [162]. By uniquely identifying entities (such as cultural artifacts, creators, institutions, places, or events) and drawing typified (e.g., temporal, spatial, contextual, and conceptual) links between them, linked data initiatives weave CH-specific knowledge graphs and relational tissues into the semantic web [163]. Corresponding applications can benefit from this extended data ecosystem by utilizing and visualizing connections that go far beyond the scope of any local CH database. As linked data also brings along the risk of opening too many doors of possible connections for the users' cognition, related projects always have to balance the chances with parallel risks of accelerating "museum fatigue" [164] in a digital setting.

Options for operationalization: Linked data can help to fundamentally reframe the interface to CH collections. In this sense, we see a remarkable potential to challenge the "authoritarian" or institutional cores of metadata inventories, as well as to conceive new avenues for visualizing object and art collections in relation to various societal environments (cf. [165]). Such contextualizations can foster a more systemic understanding of the arts and their interplay with historical environments. By connecting a given collection and its visualization with relevant societal environments in their historical constellations, the arts become visible as part of a greater system (e.g., reacting to or anticipating and influencing societal developments). CH visualizations can be annotated with historical markup, and thus contextualized within the wider socio-political circumstances of the collection's past and present [83]. But also the exchange of impulses with other societal spheres, such as politics, technology, economy, religion, science, or daily life (cf. [166]) can become visible in the rich depictions of future interfaces. In this regard, contextualizing and linking data can be a step towards further widening the concept of generosity, and to merge the horizon of CH exploration and interpretation with the complex horizons of socio-cultural meaning production and their dynamics at large.

6 Conclusion and Outlook

With this paper, we investigated and analyzed the state of the art in visual interface design for CH collection data. From the InfoVis point of view, CH data collections unfold as a specifically challenging but also promising research scenario. Novel challenges emerge from the wide variety of object types and their rich and heterogeneous metadata, often associated with materially rich content and further information, which have to be made accessible to diverse users with different abilities and aspirations.

We analyzed 70 CH visualization systems across a custom-made taxonomy to capture the current state of interface and visualization design. We analyzed the structure of this design space and reflected on open challenges and emerging topics from a wider InfoVis and humanities perspective. As such, we aimed to contribute to the consolidation of a hitherto scattered but vibrant research field. From the further development of its technical standards, we expect contributions with relevance for different communities, including scholarly, educational, intercultural, casual and public fields of cultural reasoning and communication.

To provide effective and productive interface technologies, the thorough understanding of users' motives, backgrounds, and cognitive requirements seems indispensable. As such, we argue for specifically attentive approaches, where user-centered design practices are guiding the system development, and local data, user, and task diversity is fully taken into account. While conducting this survey, we—as an interdisciplinary team of researchers with roots in different epistemic cultures—experienced once more, how only a patient collective sensemaking process can establish relevant categories and connections, which foster productive reflections between experts for information technologies and humanist thinking.

We consider visualizations and interfaces to CH data to be contemporary cultural artifacts in their own right. As they become part of our present day collection of instruments to explore, interpret, and communicate the past, we consider them even more so as epistemic objects, which need to be open for interpretation and critique. We hope that the outlined categories and principles can advance this endeavor. At the same time, we want to emphasize the need for more systematic and elaborate evaluations, which have to complement the process of interpretation and critique. It is our impression that such a balanced discourse and research design offers the unique opportunity to establish the productive connections and common languages, which will transfer a multitude of visualization endeavors into a transdisciplinary knowledge realm.

Appendix A

Online browser for the exploration of CH visualization interfaces: http://ieg.ifs.tuwien.ac.at/~federico/CHVis/

Acknowledgments

This work was supported by a grant from the Austrian Science Fund (FWF) Project No. P28363-24, and by a grant from the German Federal Ministry of Education and Research (BMBF) for the project VIKUS - Visualisierung kultureller Sammlungen. The authors wish to thank Florian Kräutli, Devon Schiller, and Florian Wienczek for their support.

References

[1] J. Henrich and R. McElreath, "The evolution of cultural evolution," *Evolutionary Anthropology: Issues, News, and Reviews*, vol. 12, no. 3, pp. 123–135, 2003.
[2] P. Richerson and R. Boyd, "Not by genes alone: How culture transformed human evolution," *Journal of Bioeconomics*, vol. 10, no. 2, pp. 193–198, 2008.
[3] S. S. Lazinger, *Digital Preservation and Metadata: History, Theory, Practice*. ERIC, 2001.
[4] F. Cameron and S. Kenderdine, *Theorizing Digital Cultural Heritage: A Critical Discourse*. Mit Press, 2007.
[5] Y. Kalay, T. Kvan, and J. Affleck, *New Heritage: New Media and Cultural Heritage*. Routledge, Nov. 2007.
[6] R. Parry, *Recoding the Museum: Digital Heritage and the Technologies of Change*. London ; New York: Routledge, 2007.
[7] M. V. Cloonan, *Preserving our Heritage: Perspectives from Antiquity to the Digital Age*. Chicago: ALA Neal-Schuman, Dec. 2014.
[8] A. L. Kroeber and C. Kluckhohn, "Culture: A critical review of concepts and definitions," *Papers. Peabody Museum of Archaeology & Ethnology, Harvard University*, 1952.
[9] R. Williams, *Keywords: A Vocabulary of Culture and Society*. Oxford University Press, USA, May 1985.

[10] W. H. Sewell Jr, "The concept(s) of culture," in *Practicing History: New Directions in Historical Writing after the Linguistic Turn*, Spiegel, Ed. Routledge, 2005, pp. 76–95.

[11] M. Arnold, *Culture and Anarchy: With Friendship's Garland and Some Literary Essays*, ser. Culture and Anarchy, R. H. Super, Ed. The University of Michigan Press, 1965, vol. 5.

[12] E. B. Tylor, *Primitive Culture: Researches into the Development of Mythology, Philosophy, Religion, Art, and Custom*. J. Murray, 1871.

[13] D. Swartz, *Culture and Power: The Sociology of Pierre Bourdieu*. University of Chicago Press, 2012.

[14] C. Calhoun, *Critical Social Theory: Culture, History, and the Challenge of Difference*, 1st ed. Cambridge, Mass: Wiley-Blackwell, Aug. 1995.

[15] Y. Ahmad, "The scope and definitions of heritage: From tangible to intangible," *International Journal of Heritage Studies*, vol. 12, no. 3, pp. 292–300, 2006.

[16] International Council on Monuments and Sites, "Historic gardens, The Florence charter, Florence, Italy," 1982.

[17] S. Ruecker, M. Radzikowska, and S. Sinclair, *Visual Interface Design for Digital Cultural Heritage: A Guide to Rich-prospect Browsing*. Ashgate Publishing, Ltd., 2011.

[18] M. Whitelaw, "Generous interfaces for digital cultural collections," *Digital Humanities Quarterly*, vol. 9, no. 1, 2015.

[19] C. A. Sula, "Quantifying culture: Four types of value in visualisation," in *Electronic Visualisation in Arts and Culture*, J. Bowen, S. Keene, and K. Ng, Eds. Springer, 2013, vol. Springer Series on Cultural Computing, pp. 25–37.

[20] K. Kontiza, A. Bikakis, and R. Miller, "Cognitive-based visualization of semantically structured cultural heritage data," in *Proc. ISWC Workshop on Visualization and Interaction for Ontologies and Linked Data*, 2015.

[21] D. Walsh, P. Clough, and J. Foster, "User categories for digital cultural heritage," in *Proc. Int. Workshop Accessing Cultural Heritage at Scale*, 2016.

[22] E. Mayr, P. Federico, S. Miksch, G. Schreder, M. Smuc, and F. Windhager, "Visualization of cultural heritage data for casual users," in *Proc. Workshop on Visualization for the Digital Humanities (vis4dh)*. Baltimore, MD.: IEEE VIS, 2016.

[23] Google arts & culture. [Online]. Available: https://www.google.com/culturalinstitute/beta/

[24] U. Hinrichs, H. Schmidt, and S. Carpendale, "EMDialog: Bringing information visualization into the museum," *IEEE Transactions on Visualization and Computer Graphics*, vol. 14, no. 6, pp. 1181–1188, 2008.

[25] Whistler & Roussell: Linked visions. [Online]. Available: http://linkedvisions.artic.edu/

[26] ECLAP linked open graph. [Online]. Available: http://www.digitalmeetsculture.net/article/eclap-social-graph/

[27] R. Simon, L. Isaksen, E. Barker, and P. de Soto Cañamares, "Peripleo: a tool for exploring heterogeneous data through the dimensions of space and time," *Code4Lib*, no. 31, 2016.

[28] W. Xu, M. Esteva, S. D. Jain, and V. Jain, "Interactive visualization for curatorial analysis of large digital collection," *Information Visualization*, vol. 13, no. 2, pp. 159–183, 2014.

[29] Museum of the world. [Online]. Available: https://britishmuseum.withgoogle.com/

[30] D. Goldfarb, M. Arends, J. Froschauer, and D. Merkl, "Revisiting 3D information landscapes for the display of art historical web content (ace)," in *Proc. Int. Conf. on Advances in Computer Entertainment Technology*. New York, NY, USA: ACM, 2011, pp. 46:1–46:8.

[31] MoMa. Inventing abstraction 1910–1925 | MoMA. [Online]. Available: http://www.moma.org/interactives/exhibitions/2012/inventingabstraction/

[32] Your uncertain archive. [Online]. Available: http://olafureliasson.net/uncertain

[33] D. Crockett, "Direct visualization techniques for the analysis of image data: The slice histogram and the growing entourage plot," *International Journal for Digital Art History*, vol. 0, no. 2, 2016.

[34] P. Federico, F. Heimerl, S. Koch, and S. Miksch, "A survey on visual approaches for analyzing scientific literature and patents," *IEEE Transactions on Visualization and Computer Graphics*, vol. 23, no. 9, pp. 2179–2198, Sept 2017.

[35] S. Jänicke, J. Focht, and G. Scheuermann, "Interactive visual profiling of musicians," *IEEE Transactions on Visualization and Computer Graphics*, vol. 22, no. 1, pp. 200–209, 2016.

[36] M. Schich, C. Song, Y.-Y. Ahn, A. Mirsky, M. Martino, A.-L. Barabsi, and D. Helbing, "A network framework of cultural history," *Science*, vol. 345, no. 6196, pp. 558–562, Aug. 2014.

[37] I. Cho, W. Dou, D. X. Wang, E. Sauda, and W. Ribarsky, "VAiRoma: A visual analytics system for making sense of places, times, and events in roman history," *IEEE Transactions on Visualization and Computer Graphics*, vol. 22, no. 1, pp. 210–219, 2016.

[38] Histography.io. [Online]. Available: http://histography.io/

[39] DARIAH-DE geo-browser. [Online]. Available: https://geobrowser.de.dariah.eu/

[40] Palladio |Humanities+Design Stanford. [Online]. Available: http://hdlab.stanford.edu/palladio/#/

[41] S. Jänicke, C. Heine, and G. Scheuermann, "GeoTemCo: Comparative visualization of geospatial-temporal data with clutter removal based on dynamic Delaunay triangulations," in *Proc. Int. Joint Conf. Computer Vision, Imaging and Computer Graphics. Theory and Application (VISIGRAPP)*. Springer, 2013, pp. 160–175.

[42] J. Ma, I. Liao, K. L. Ma, and J. Frazier, "Living Liquid: Design and evaluation of an exploratory visualization tool for museum visitors," *IEEE Transactions on Visualization and Computer Graphics*, vol. 18, no. 12, pp. 2799–2808, 2012.

[43] J. Zhang, K. Kang, D. Liu, Y. Yuan, and E. Yanli, "Vis4heritage: visual analytics approach on grotto wall painting degradations," *IEEE Transactions on Visualization and Computer Graphics*, vol. 19, no. 12, pp. 1982–1991, 2013.

[44] S. Miksch and W. Aigner, "A matter of time: Applying a data-users-tasks design triangle to visual analytics of time-oriented data," *Computers & Graphics*, vol. 38, pp. 286–290, 2014.

[45] T. Munzner, "A nested model for visualization design and validation," *IEEE Transactions on Visualization and Computer Graphics*, vol. 15, no. 6, pp. 921–928, Nov 2009.

[46] C. Meghini, *Definition of the Europeana Data Model v5.2.7*, Europeana Foundation, 2016.

[47] *Dublin Core Metadata Element Set, Version 1.1*, Dublin Core Metadata Initiative, 2012.

[48] H. Van de Sompel and C. Lagoze, "Interoperability for the discovery, use, and re-use of units of scholarly communication," *CTWatch Quarterly*, vol. 3, no. 3, pp. 32–41, 2007.

[49] A. Miles and S. Bechhofer, *SKOS Simple Knowledge Organization System Reference*, World Wide Web Consortium, 2009.

[50] *The CIDOC Conceptual Reference Model*, International Council of Museums, 2003.

[51] *Metadata Application Profile, version 4.0*, Digital Public Library of America, 2015.

[52] A. Thudt, U. Hinrichs, and S. Carpendale, "The Bohemian bookshelf: Supporting serendipitous book discoveries through information visualization," in *Proc. SIGCHI Conf. on Human Factors in Computing Systems (CHI)*. New York: ACM, 2012, pp. 1461–1470.

[53] V. de Boer, J. Oomen, O. Inel, L. Aroyo, E. van Staveren, W. Helmich, and D. de Beurs, "DIVE into the event-based browsing of linked historical media," *Web Semantics: Science, Services and Agents on the World Wide Web*, vol. 35, Part 3, pp. 152–158, Dec. 2015.

[54] M. Addis, K. Matrinez, P. Lewis, J. Stevenson, and F. Girogini, "New ways to search, navigate and use multimedia museum collections over the web," in *Proc. Museums & the Web*. Toronto: Archives & Museum Informatics, 2005.

[55] J. L. Klavans, C. Sheffield, E. Abels, J. Lin, R. Passonneau, T. Sidhu, and D. Soergel, "Computational linguistics for metadata building (CLiMB): Using text mining for the automatic identification, categorization, and disambiguation of subject terms for image metadata," *Multimedia Tools and Applications*, vol. 42, no. 1, 2009.

[56] S. Hinton and M. Whitelaw, "Exploring the digital commons: An approach to the visualisation of large heritage datasets," in *Proc. Int. Conf. on Electronic Visualisation and the Arts*. British Computer Society, 2010, pp. 51–58.

[57] J. Novak, I. Micheel, M. Melenhorst, L. Wieneke, M. Düring, J. G. Morón, C. Pasini, M. Tagliasacchi, and P. Fraternali, "HistoGraph – A visualization tool for collaborative analysis of networks from historical social multimedia collections," in *Proc. Int. Conf. Information Visualisation (IV)*. IEEE, 2014, pp. 241–250.

[58] B. Saleh and A. Elgammal, "Large-scale classification of fine-art paintings: Learning the right metric on the right feature," *International Journal for Digital Art History*, vol. 0, no. 2, 2016.

[59] H. Pflüger and T. Ertl, "Sifting through visual arts collections," *Computers & Graphics*, vol. 57, pp. 127 – 138, 2016.

[60] Z. Pousman, J. Stasko, and M. Mateas, "Casual information visualization: Depictions of data in everyday life," *IEEE Transactions on Visualization and Computer Graphics*, vol. 13, no. 6, 2007.

[61] M. Koolen, J. Kamps, and V. de Keijzer, "Information retrieval in cultural heritage," *Interdisciplinary Science Reviews*, vol. 34, no. 2-3, pp. 268–284, 2009.

[62] D. Walsh and M. M. Hall, "Just looking around: Supporting casual users initial encounters with Digital Cultural Heritage," in *Proc. ECIR Workshop on Supporting Complex Search Tasks*, vol. 1338. Vienna: CEUR-WS, 2015.

[63] R. Villa, P. D. Clough, M. M. Hall, and S. A. Rutter, "Search or browse? Casual information access to a cultural heritage collection," in *Proc. European Workshop on Human-Computer Interaction and Information Retrieval*, vol. 1033. CEUR-WS, 2013, pp. 19–22.

[64] M. Mauri, A. Pini, D. Ciminieri, and P. Ciuccarelli, "Weaving data, slicing views: A design approach to creating visual access for digital archival collections," in *Proc. Biannual Conf. of the Italian Chapter of SIGCHI*. ACM, 2013, p. 21.

[65] U. Hinrichs, S. Forlini, and B. Moynihan, "Speculative practices: Utilizing InfoVis to explore untapped literary collections," *IEEE Transactions on Visualization and Computer Graphics*, vol. 22, no. 1, pp. 429–438, 2016.

[66] E. Mäkelä, E. Hyvönen, and T. Ruotsalo, "How to deal with massively heterogeneous cultural heritage data – Lessons Learned in CultureSampo," *Semantic Web*, vol. 3, no. 1, pp. 85–109, 2012.

[67] S. Yamaoka, L. Manovich, J. Douglass, and F. Kuester, "Cultural analytics in large-scale visualization environments," *Computer*, vol. 44, no. 12, pp. 39–48, Dec. 2011.

[68] L. Algee, J. Bailey, and T. Owens, "Viewshare and the Kress Collection: Creating, sharing, and rapidly prototyping visual interfaces to cultural heritage collection data," *D-Lib Magazine*, vol. 18, no. 11, p. 3, 2012.

[69] M. Douma, G. Ligierko, and J. Romano, "Concept Maps for online exhibits: Using SpicyNodes," in *Proc. Museums & the Web*. Toronto: Archives & Museum Informatic, 2010.

[70] B. Nowviskie, D. McClure, W. Graham, A. Soroka, J. Boggs, and E. Rochester, "Geo-temporal interpretation of archival collections with Neatline," *Lit Linguist Computing*, vol. 28, no. 4, pp. 692–699, 2013.

[71] N. Andrienko and G. Andrienko, *Exploratory Analysis of Spatial and Temporal Data: A Systematic Approach*. Berlin, Heidelberg: Springer, 2006.

[72] M. Dörk, C. Pietsch, and G. Credico, "One view is not enough. High-level visualizations of a large cultural collection," *Information Design Journal*, vol. 23:1, pp. 39–47, 2017.

[73] M. Dörk, S. Carpendale, and C. Williamson, "The information flaneur: A fresh look at information seeking," in *Proc. SIGCHI Conference on Human Factors in Computing Systems*. ACM, 2011, pp. 1215–1224.

[74] S. Greene, G. Marchionini, C. Plaisant, and B. Shneiderman, "Previews and overviews in digital libraries: Designing surrogates to support visual information seeking," *Journal of the American Society for Information Science*, vol. 51, no. 4, pp. 380–393, 2000.

[75] B. E. Butler, "Visual exploration of Australian prints and printmaking," in *Proc. Museums & the Web*. Toronto: Archives & Museum Informatic, 2013.

[76] J. Coburn, "I don't know what I' looking for: Better understanding public usage and behaviours with Tyne & Wear Archives & Museums online collections," in *Proc. Museums & the Web*. Toronto: Archives & Museum Informatics, 2016.

[77] NYPL Public Domain Release 2016 - Visualization. [Online]. Available: http://publicdomain.nypl.org/pd-visualization/

[78] M. Dörk, N. H. Riche, G. Ramos, and S. Dumais, "Pivotpaths: Strolling through faceted information spaces," *IEEE Transactions on Visualization and Computer Graphics*, vol. 18, no. 12, pp. 2709–2718, 2012.

[79] M. J. Bates, "The design of browsing and berrypicking techniques for the online search interface," *Online Information Review*, vol. 13, no. 5, pp. 407–424, 1989.

[80] W. Aigner, S. Miksch, H. Schumann, and C. Tominski, *Visualization of Time-oriented Data*. Springer Science & Business Media, 2011.

[81] F. Kräutli, "Visualising cultural data: Exploring digital collections through timeline visualisations," Ph.D. dissertation, Royal College of Art, London, UK, 2016.

[82] F. Kräutli and B. Davis, S., "Revealing cultural collections over time," in *Proc. EG UK Computer Graphics & Visual Computing*, R. Borgo and C. Turkay, Eds. London: The Eurographics Association, 2015.

[83] K. Glinka, C. Pietsch, and M. Dörk, "Past visions and reconciling views: Visualizing time, texture and themes in cultural collections," *Digital Humanities Quarterly*, vol. 11, no. 2, 2017.

[84] A. Capodieci, D. D'Aprile, G. Elia, F. Grippa, and L. Mainetti, "Visualizing cultural digital resources using social network analysis," in *Proc. Int. Joint Conf. on Knowledge Discovery, Knowledge Engineering and Knowledge Management (IC3K)*, vol. 01, 2015, pp. 186–194.

[85] B. Dumas, B. Moerman, S. Trullemans, and B. Signer, "ArtVis: Combining advanced visualisation and tangible interaction for the exploration, analysis and browsing of digital artwork collections," in *Proc. Int. Working Conf. Advanced Visual Interfaces (AVI)*. ACM, 2014, pp. 65–72.

[86] M. Burch, U. Kloos, I. Hagen, R. Horst, L. Brand, A. Müller, and B. Weinert, "artVIS: An interactive visualization for painting collections," in *Proc. Int. Symposium on Visual Information Communication and Interaction (VINCI)*. Bangkok: ACM, 2017.

[87] M.-J. Kraak, "Timelines, temporal resolution, temporal zoom and time geography," in *Proc. Int. Cartographic Conf.*, 2005.

[88] F. Windhager and E. Mayr, "Cultural heritage cube. A conceptual framework for visual exhibition exploration," in *Proc. Int. Conf Information Visualisation (IV)*, 2012, pp. 540 –545.

[89] Mapping Titian. [Online]. Available: http://www.mappingpaintings.org/

[90] A. Betti, T. H. A. Castermans, B. Speckmann, H. van den Berg, and K. A. B. Verbeek, "GlamMapping trove," in *Proc. VALA Biennial Conf. and Exhibition*, 2016.

[91] V. Deufemia, L. Paolino, G. Tortora, A. Traverso, V. Mascardi, M. Ancona, M. Martelli, N. Bianchi, and H. De Lumley, "Investigative analysis across documents and drawings: Visual analytics for archaeologists," in *Proc. Int. Working Conf. Advanced Visual Interfaces (AVI)*. New York: ACM, 2012, pp. 539–546.

[92] R. Damiano, V. Lombardo, and A. Lieto, "Visual metaphors for semantic cultural heritage," in *Proc. Int. Conf. on Intelligent Technologies for Interactive Entertainment (INTETAIN)*, Jun. 2015, pp. 100–109.

[93] R. Shen, N. S. Vemuri, W. Fan, R. da S. Torres, and E. A. Fox, "Exploring digital libraries: Integrating browsing, searching, and visualization," in *Proc. ACM/IEEE-CS Joint Conference on Digital Libraries (JCDL)*. New York, NY, USA: ACM, 2006, pp. 1–10.

[94] L. Manovich, "Cultural analytics: Visualising cultural patterns in the era of more media," *Domus March*, 2009.

[95] K. Albrecht, M. Dörk, and B. Müller, "Culturegraphy," *Leonardo*, 2016.

[96] G. Ciocca, P. Olivo, and R. Schettini, "Browsing museum image collections on a multi-touch table," *Information Systems*, vol. 37, no. 2, pp. 169–182, Apr. 2012.

[97] R. J. Urban, M. B. Twidale, and P. D. Adamczyk, "Designing and developing a collections dashboard," in *Proc. Museums & the Web*. Toronto: Archives & Museum Informatic, 2010.

[98] L. Rajaonarivo, M. Courgeon, E. Maisel, and P. De Loor, "Inline co-evolution between users and information presentation for data exploration," in *Proc. Int. Conf. on Intelligent User Interfaces (IUI)*. Limaddol, Cyprus: ACM, 2017, pp. 215–219.

[99] E. Ruffaldi, C. Evangelista, V. Neri, M. Carrozzino, and M. Bergamasco, "Design of information landscapes for cultural heritage content," in *Proc. Int. Conf. on Digital Interactive Media in Entertainment and Arts (DIMEA)*. New York: ACM, 2008, pp. 113–119.

[100] P. Brivio, M. Tarini, and P. Cignoni, "Browsing large image datasets through Voronoi diagrams," *IEEE Transactions on Visualization and Computer Graphics*, vol. 16, no. 6, pp. 1261–1270, Nov. 2010.

[101] O. O. Buchel, "Designing map-based visualizations for collection understanding," in *Proc. ACM/IEEE Joint Conf. on Digital Libraries (JCDL)*. New York: ACM, 2011, pp. 429–430.

[102] L. Deal, "Visualizing digital collections," *Technical Services Quarterly*, vol. 32, no. 1, pp. 14–34, 2015.

[103] M. Chang, J. J. Leggett, R. Furuta, A. Kerne, J. P. Williams, S. A. Burns, and R. G. Bias, "Collection understanding," in *Proc. ACM/IEEE-CS Joint Conference on Digital Libraries (JCDL)*. New York: ACM, 2004, pp. 334–342.

[104] M. Burch, U. Kloos, D. Junger, I. Hagen, R. Horst, L. Brand, A. Müuller, and B. Weinert, "artVIS: An interactive visualization for painting collections," in *Proc. Int. Symposium on Visual Information Communication and Interaction (VINCI)*, 2017.

[105] T. Berg-Fulton, D. Newbury, and T. Snyder, "Art Tracks: Visualizing the stories and lifespan of an artwork," in *Proc. Museums & the Web*. Toronto: Archives & Museum Informatic, 2015.

[106] R. A. Haubt and P. S. C. Taçon, "A collaborative, ontological and information visualization model approach in a centralized rock art heritage platform," *Journal of Archaeological Science: Reports*, vol. 10, pp. 837–846, Dec. 2016.

[107] S. Kenderdine and T. Hart, "mARChive: Sculpting Museum Victorias collections," in *Proc. Museums & the Web*. Toronto: Archives & Museum Informatic, 2014.

[108] J. Kramer-Smyth, M. Nishigaki, and T. Anglade, "ArchivesZ: Visualizing archival collections," University of Maryland, Tech. Rep., 2007.

[109] K. Rogers, U. Hinrichs, and A. Quigley, "It doesn't compare to being there: In-situ vs. remote exploration of museum collections," in *Proc. Workshop on Exploring Cultural Collections with Visualization*, 2014.

[110] C. Seifert, J. Jurgovsky, and M. Granitzer, "FacetScape: A visualization for exploring the search space," in *Proc. Int. Conf. Information Visualisation (IV)*. IEEE, 2014, pp. 94–101.

[111] R. Theron, C. Segun, L. de la Cruz, and M. Vaquero, "Highly interactive and natural user interfaces: Enabling visual analysis in historical lexicography," in *Proc. Int. Conf. on Digital Access to Textual Cultural Heritage (DATeCH)*. New York: ACM, 2014, pp. 153–158.

[112] L. Crissaff, L. W. Ruby, S. Deutch, R. L. DuBois, J. D. Fekete, J. Freire, and C. Silva, "ARIES: Enabling visual exploration and organization of art image collections," *IEEE Computer Graphics and Applications*, vol. PP, no. 99, pp. 1–1, 2017.

[113] MET timeline of art history. [Online]. Available: http://www.metmuseum.org/toah/chronology/

[114] Mapping the republic of letters. [Online]. Available: http://ink.designhumanities.org/dalembert/

[115] selfiexploratory.

[116] SFMoMA ArtScope. [Online]. Available: https://www.sfmoma.org/experience/artscope/#r=64

[117] Digital public library of America. [Online]. Available: https://dp.la/timeline

[118] Object:Photo | MoMA. [Online]. Available: https://www.moma.org/interactives/objectphoto/#home

[119] Historypin. [Online]. Available: https://www.historypin.org/en/

[120] ResearchSpace. [Online]. Available: https://public.researchspace.org/

[121] The Australian dress register. [Online]. Available: http://www.australiandressregister.org/timeline/

[122] VIJKS. Visualizing the Rijksmuseum. [Online]. Available: http://www.vijks.com/

[123] S. De Caro, N. Di Blas, and L. Spagnolo, "In search of novel ways to design large cultural web sites," in *Proc. Museums & the Web*. Toronto: Archives & Museum Informatics, 2010.

[124] P. Goodale, "Individual differences in exploration and content curation activities within a cultural heritage digital library," in *Proc. Int. Workshop Accessing Cultural Heritage at Scale*, vol. 1611. CEUR-WS, 2016, p. paper 8.

[125] N. Kerracher, J. Kennedy, and K. Chalmers, "The design space of temporal graph visualisation," in *Proc. Eurographics Conf. on Visualization (EuroVis)*, vol. Short. Swansea: Eurographics Assocation, 2014.

[126] M. Sedlmair, K. Ruhland, F. Hennecke, A. Butz, S. Bioletti, and C. O'Sullivan, "Towards the big picture: Enriching 3d models with information visualisation and vice versa," in *Proc. Int. Symposium Smart Graphics*. Springer, 2009, pp. 27–39.

[127] UNESCO list of intangible cultural heritage. [Online]. Available: https://ich.unesco.org/en/lists

[128] Merriam Webster dictionary.

[129] A. Foster and N. Ford, "Serendipity and information seeking: An empirical study," *Journal of Documentation*, vol. 59, no. 3, pp. 321–340, 2003.

[130] S. Makri, A. Blandford, M. Woods, S. Sharples, and D. Maxwell, "Making my own luck: Serendipity strategies and how to support them in digital information environments," *Journal of the Association for Information Science and Technology*, vol. 65, no. 11, pp. 2179–2194, 2014.

[131] S. Chan, "Tagging and searching – Serendipity and museum collection databases," in *Proc. Museums & the Web*, J. Trant and D. Bearman, Eds. Toronto: Archives & Museum Informatics, 2007.

[132] E. Kleiner, R. Rädle, and H. Reiterer, "Blended shelf: Reality-based presentation and exploration of library collections," in *CHI Extended Abstracts on Human Factors in Computing Systems (CHI EA)*. New York: ACM, 2013, pp. 577–582.

[133] E. G. Toms and L. McCay-Peet, "Chance encounters in the digital library," in *Proc. European Conf. Research and Advanced Technology for Digital Libraries (ECDL)*, M. Agosti, J. Borbinha, S. Kapidakis, C. Papatheodorou, and G. Tsakonas, Eds. Berlin, Heidelberg: Springer, 2009, pp. 192–202.

[134] P. W. Andrew Garbett and T. Bartindale. (2015) Past paths – Reconceptualising the online museum experience.

[135] R. Melo and M. Carvalhais, "Regarding value in digital serendipitous interactions," *Journal of Science and Technology of the Arts*, vol. 8, no. 2, pp. 37–44, 2016.

[136] B. Shneiderman, "The eyes have it: A task by data type taxonomy for information visualizations," in *Proc. IEEE Symposium on Visual Languages*. IEEE Computer Society, 1996, p. 336.

[137] J. Drucker, "Performative materiality and theoretical approaches to interface," *Digital Humanities Quarterly*, vol. 7, no. 1, 2013.

[138] ——, "Humanities Approaches to Graphical Display," *Digital Humanities Quarterly*, vol. 5, no. 1, pp. 1–21, 2011.

[139] ——, "Humanities approaches to interface theory," *Culture Machine*, vol. 12, 2011.

[140] F. Windhager, K. Glinka, E. Mayr, G. Schreder, and M. Dörk, "Zur Weiterentwicklung des cognition support: Sammlungsvisualisierungen als Austragungsort kritisch-kulturwissenschaftlicher Forschung," in *Digital Humanities im deutschsprachigen Raum (DHd)*, 2018.

[141] M. Dörk, P. Feng, C. Collins, and S. Carpendale, "Critical InfoVis: Exploring the politics of visualization," in *CHI Extended Abstracts on Human Factors in Computing Systems (CHI EA)*. ACM, 2013, pp. 2189–2198.

[142] J. Hullman and N. Diakopoulos, "Visualization rhetoric: Framing effects in narrative visualization," *IEEE Transactions on Visualization and Computer Graphics*, vol. 17, no. 12, pp. 2231–2240, 2011.

[143] A. L. Jones, "Exploding canons: The anthropology of museums," *Annual Review of Anthropology*, vol. 22, pp. 201–220, 1993.

[144] K. Glinka, S. Meier, and M. Dörk, "Visualising the Un-seen: Towards critical approaches and strategies of inclusion in digital cultural heritage interfaces," in *Kultur und Informatik (XIII) - Cross Media*, C. Busch and J. Sieck, Eds. Berlin: Werner Hülsbusch, 2015, pp. 105–118.

[145] K. Schoeffmann and D. Ahlström, "Similarity-based visualization for image browsing revisited," in *Proc. IEEE Int. Workshop on Multimedia Information Processing and Retrieval (MIPR)*. New York: IEEE, 2011, pp. 422–427.

[146] M. Sanderhoff, "Open images. Risk or opportunity for art collections in the digital age?" *Nordisk Muesologi*, no. 2, pp. 131–146, 2013.

[147] E. Segel and J. Heer, "Narrative visualization: Telling stories with data," *IEEE Transactions on Visualization and Computer Graphics*, vol. 16, no. 6, pp. 1139–1148, Nov 2010.

[148] R. Kosara and J. Mackinlay, "Storytelling: The next step for visualization," *Computer*, vol. 46, no. 5, pp. 44–50, 2013.

[149] B. Lee, N. H. Riche, P. Isenberg, and S. Carpendale, "More than telling a story: Transforming data into visually shared stories," *IEEE Computer Graphics and Applications*, vol. 35, no. 5, pp. 84–90, 2015.

[150] S. B. Davis, O. Vane, and F. Kräutli, "Using data visualisation to tell stories about collections," in *Proc. Electronic Visualisation and the Arts (EVA)*, G. D. . N. L. J. P. Bowen, Ed. London: BCS Learning and Development Ltd., 2016.

[151] R. Eccles, T. Kapler, R. Harper, and W. Wright, "Stories in GeoTime," *Information Visualization*, vol. 7, no. 1, pp. 3–17, 2008.

[152] U. Hinrichs, S. Butscher, J. Mller, and H. Reiterer, "Diving in at the deep end: The value of alternative in-situ approaches for systematic library search," in *Proc. SIGCHI Conf. on Human Factors in Computing Systems (CHI)*. ACM, 2016, pp. 4634–4646.

[153] J. Alexander, "Gallery One, the First year: Sustainability, evaluation process, and a new smart phone app," in *Proc. Museums & the Web*, 2014.

[154] M. Carrozzino and M. Bergamasco, "Beyond virtual museums: Experiencing immersive virtual reality in real museums," *Journal of Cultural Heritage*, vol. 11, no. 4, pp. 452–458, Oct. 2010.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2018.2830759, IEEE Transactions on Visualization and Computer Graphics

[155] A. Damala, E. Hornecker, M. van der Vaart, D. van Dijk, and I. Ruthven, "The Loupe: Tangible augmented reality for learning to look at ancient Greek art," *Mediterranean Archaeology and Archaeometry*, vol. 16, no. 5, pp. 73–85, 2016.

[156] G.-P. Bonneau, H.-C. Hege, C. R. Johnson, M. M. Oliveira, K. Potter, P. Rheingans, and T. Schultz, "Overview and state-of-the-art of uncertainty visualization," in *Scientific Visualization. Uncertainty, Multifield, Biomedical, and Scalable Visualization*, ser. Mathematics and Visualization, C. e. a. Hansen, Ed. Springer International Publishing, 2014, no. 9114, pp. 3–23.

[157] F. I. Apollonio, *Classification Schemes for Visualization of Uncertainty in Digital Hypothetical Reconstruction*. Cham: Springer International Publishing, 2016, pp. 173–197.

[158] F. Kräutli and S. Boyd Davis, "Known unknowns: Representing uncertainty in historical time," in *Proc. Workshop on Electronic Visualisation and the Arts*, 2013.

[159] T. Gschwandtner, M. Bögl, P. Federico, and S. Miksch, "Visual encodings of temporal uncertainty: A comparative user study," *IEEE Transactions on Visualization and Computer Graphics*, vol. 22, no. 1, pp. 539–548, Jan 2016.

[160] S. Jänicke, G. Franzini, M. F. Cheema, and G. Scheuermann, "Visual text analysis in digital humanities," *Computer Graphics Forum*, vol. 36, no. 6, pp. 226–250, 2017.

[161] S. v. Hooland and R. Verborgh, *Linked Data for Libraries, Archives and Museums: How to Clean, Link and Publish your Metadata*. Facet Publishing, Jun. 2014.

[162] D. Oldman, M. Doerr, and S. Gradmann, "Zen and the art of linked data," in *A New Companion to Digital Humanities*, S. Schreibman, R. Siemens, and J. Unsworth, Eds. John Wiley & Sons, Ltd, 2016, pp. 251–273.

[163] P. Szekely, C. A. Knoblock, F. Yang, X. Zhu, E. E. Fink, R. Allen, and G. Goodlander, "Connecting the Smithsonian American art museum to the linked data cloud," in *Proc. Extended Semantic Web Conference*. Springer, 2013, pp. 593–607.

[164] G. Davey, "What is museum fatigue?" *Visitor Studies Today*, vol. 8, no. 3, pp. 17–21, 2005.

[165] F. Windhager, E. Mayr, G. Schreder, and M. Smuc, "Linked information visualization for linked open government data. A visual synthetics approach to governmental data and knowledge collections," *JeDEM - eJournal of eDemocracy and Open Government*, vol. 8, no. 2, pp. 87–115, Dec. 2016.

[166] H. Kräutler, "Rondom Rembrandt and beyond: On Otto Neuraths isotype contributions to visual communication and museum learning," *Publications of the Austrian Ludwig Wittgenstein Society - New Series (Volumes 1-18)*, vol. 17, 2013.

Florian Windhager is a research associate at the Department for Knowledge & Communication Management at Danube University Krems, Austria. His research interests are in information visualization, digital humanities, and new fields of application for visual thinking and reasoning. He holds a Master of Philosophy from the University of Vienna, Austria, and currently aims for the development of a visual analytics framework for the area of historical and biographical data.

Paolo Federico is a postdoctoral researcher at the Institute of Software Technology and Interactive Systems, TU Wien, Austria. His main research interests are information visualization and visual analytics, in particular of time-oriented and network data. Federico holds a Masters in Telecommunications Engineering from the "Federico II" University of Naples, Italy, and a PhD in Computer Science from TU Wien, Austria.

Günther Schreder is a research associate at the Department for Knowledge & Communication Management, Danube University Krems, Austria. His research focuses on how technology can support the cognitive processes of individuals and groups. He is teaching quantitative methods, user-centered design and cognitive psychology. He holds a Master of Science in psychology from the University of Vienna, Austria.

Katrin Glinka is with the Stiftung Preussischer Kulturbesitz where she is the DH team lead for the joint project museum4punkt0. She is also a lecturer and former research associate at the University of Applied Sciences Potsdam and a PhD candidate at the Humboldt-University Berlin. As a cultural scientist, she has a focus on art, sociology, museums, and digital CH. Her research focuses on digitization and visualization and their means for curation, critical and interventionist approaches.

Marian Dörk is a Research Professor for Information Visualization at the Institute for Urban Futures of the University of Applied Sciences Potsdam. In his work, he is particularly interested in the potential of visual interfaces to support new forms of data exploration. He is the co-founder of the Urban Complexity Lab, a transdisciplinary research space dedicated to visualization research at the intersection between computing, design, and the humanities.

Silvia Miksch is University Professor at Institute of Software Technology and Interactive Systems, TU Wien. She served as paper co-chair of several conferences including IEEE VAST 2010 & 2011 and EuroVis 2012 and on the editorial board of several journals including IEEE TVCG. She acts in various strategic committees, such as the VAST steering committee and the VIS Executive Committee. Her main research interests are Visualization/Visual Analytics (particularly Focus+Context and Interaction) and Time.

Eva Mayr is a postdoctoral researcher at the Department for Knowledge & Communication Management, Danube University Krems, Austria. Her main research interests are the cognitive processes during interaction with information visualizations, in particular in "casual", informal learning settings. Eva holds a PhD in applied cognitive and media psychology from the University of Tübingen, Germany.