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for Digital Humanities

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Visualization-based Storytelling

for Digital Humanities

by

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Abstract

In the domains of digital humanities and cultural heritage, storytelling has emerged as a crucial methodology for conveying the depth and breadth of our shared history. This dissertation thesis explores the intersection of visualization and narrative techniques to embrace and present the complex matters of humanities and culture in an engaging manner. The focus lies on developing and applying storytelling strategies using visualizations to enhance the understanding and appreciation of cultural heritage in a comprehensive and systematic approach to support the iterative work with a multitude of databases, media, visualizations, and user practices in adjacent scientific and practical fields.

Exploring the intersection of digital humanities, cultural heritage, and visualization sets the stage for this thesis, wherein current tasks, shared goals, methodologies, and challenges in digitization, depiction, accessibility, management, documentation, preservation, and communication are examined.

As a means of addressing these issues, the current state of research in visualization-based storytelling is assessed by proposing a problem-specific design space for analyzing and creating appropriate communication of complex topics with humanities and cultural relevance.

An applied example of such complex matters is musicology, which deals among others with pieces of music and musical instruments. These two tangible threads of cultural heritage are interwoven with intangible traditions and now need to be visually combined and communicated. However, no explicit storytelling methods are used here yet, but rather contextualization and knowledge derivation by means of explorative visualizations and hypotheses. Thereby application-oriented collaboration with domain experts, who are involved in the development and interpretation of corresponding results, leads to untold observations of music composition and instrument making. Immersing on these stories, further aspects of musicology are explored by delving into natural materials from plants and animals in endangered ecosystems to manufacture musical instruments. These complex and fragile inter-dependencies are broad into context and visualized for experts from ecology, geography and instrument making. In contrast, to communicate these complex relationships to a broader public, the various visualizations and corresponding visual elements were reused and embedded in an interactive scrollytelling. Enriched with further multimedia elements, they tell a comprehensive story of musical instruments and their remotely linked ecosystems around the globe. In contrast to that, in a further project, people, objects, places, and communities from different nations are connected by their stories while using visualization-based storytelling to present and convey them. The resulting holistic platform unites curation, visual analysis, and communication through storytelling. To demonstrate the excellence of this approach, a variety of domain-motivated case studies explain the methodologies with different media, types of visualization, databases, and practices in an illustrative manner. Ultimately, a comprehensive discussion of experiences and research findings, as well as ongoing questions and challenges are presented. This highlights the importance of a user-centered design approach in developing visual analytics tools that are accessible and engaging to a wide range of users to enhance our understanding and appreciation of cultural heritage. This contributes to the fields by offering new insights into using visualization-based storytelling to analyze and communicate the complexities of digital humanities and cultural data.

Dansk Resumé

I den digitale humaniora og kulturarvsdomæner er storytelling fremkommet som en afgørende metode til at formidle dybden og bredden af vores fælles historie. Denne afhandling undersøger skæringspunktet mellem visualisering og narrative teknikker for at omfavne og præsentere de komplekse emner inden for humaniora og kultur på en engagerende måde. Fokus ligger på at udvikle og anvende storytelling-strategier ved hjælp af visualiseringer for at forbedre forståelsen og værdsættelsen af kulturarv på en omfattende og systematisk måde for at støtte det iterative arbejde med en mangfoldighed af databaser, medier, visualiseringer og brugerpraksis i tilgrænsende videnskabelige og praktiske felter.

Udforskningen af skæringspunktet mellem digital humaniora, kulturarv og visualisering danner grundlag for denne afhandling, hvor aktuelle opgaver, fælles mål, metoder og udfordringer inden for digitalisering, fremstilling, tilgængelighed, forvaltning, dokumentation, bevarelse og kommunikation undersøges. Som et middel til at adressere disse spørgsmål vurderes den nuværende tilstand af forskning inden for storytelling baseret på visualisering ved at foreslå et problemspecifikt designrum til analyse og skabelse af passende kommunikation af komplekse emner med humanistisk og kulturel relevans. Et anvendt eksempel på sådanne komplekse sager er musikvidenskab, som blandt andet beskæftiger sig med musikstykker og musikinstrumenter. Disse to håndgribelige tråde af kulturarv er vævet sammen med immaterielle traditioner og skal nu visuelt kombineres og kommunikeres. Der anvendes dog endnu ikke eksplicitte storytelling-metoder her, men snarere kontekstualisering og vidensderivat ved hjælp af eksplorative visualiseringer og hypoteser. Dermed fører anvendelsesorienteret samarbejde med domæneeksperter, som er involveret i udviklingen og fortolkningen af de tilsvarende resultater, til ufortalte observationer af musikkomposition og instrumentfremstilling. Ved at fordybe sig i disse historier udforskes yderligere aspekter af musikvidenskab ved at dykke ned i naturlige materialer fra planter og dyr i truede økosystemer til fremstilling af musikinstrumenter. Disse komplekse og skrøbelige indbyrdes afhængigheder bringes i kontekst og visualiseres for eksperter fra økologi, geografi og instrumentfremstilling. I modsætning til at kommunikere disse komplekse relationer til et bredere publikum blev de forskellige visualiseringer og tilhørende visuelle elementer genbrugt og indlejret i en interaktiv scrollytelling. Beriget med yderligere multimedieelementer fortæller de en omfattende historie om musikinstrumenter og deres fjerntliggende økosystemer rundt om i verden. I modsætning hertil forbinder et yderligere projekt mennesker, objekter, steder og fællesskaber fra forskellige nationer gennem deres historier, mens de bruger storytelling baseret på visualisering til at præsentere og formidle dem. Den resulterende helhedsorienterede platform forener kuratering, visuel analyse og kommunikation gennem storytelling. For at demonstrere denne tilgangs fremragenhed forklarer en række domænemotiverede casestudier metoderne med forskellige medier, visualiseringstyper, databaser og praksisser på en illustrativ måde.

Endelig præsenteres en omfattende diskussion af erfaringer og forskningsresultater samt igangværende spørgsmål og udfordringer. Dette fremhæver vigtigheden af en brugercentreret designmetode i udviklingen af visuelle analyseværktøjer, der er tilgængelige og engagerende for et bredt udvalg af brugere for at forbedre vores forståelse og værdsættelse af kulturarv. Dette bidrager til felterne ved at tilbyde nye indsigter i brugen af storytelling baseret på visualisering til at analysere og kommunikere kompleksiteterne af digital humaniora og kulturelle data.

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I've been incredibly lucky to work on my passions and meet amazing experts and friends along the way.

I would like to express my sincere gratitude to Stefan as my PhD supervisor for always believing in me and giving me motivating advice. I'm also grateful for the guidance of other fantastic supervisors, especially Florian, Eva, David, Tom, Josef and Heike. Working with Silke on our MusEcology project has been a highlight, thanks to her endless ideas and understanding of our collaborative work.

I couldn't have asked for better friends than Richard and Christopher, who have been with me throughout my studies and have given me unwavering support. My colleagues, especially Christofer, Johannes, Samuel and Stefan, have made my projects enlightening, enjoyable and fulfilling. Nicho, Louis and Paula have been like family and have supported me throughout my studies. I cherish the friendships, all the informed exchanges and fun times with my colleagues Gareth, Esben, William, Nicklas, Birthe and Sebastian, who kept me motivated even when things were tough. I'm excited about what the future holds for our research!

Finally, I am grateful to my family, Ulrike, Sebastian, Johanna and Jonathan. They have enabled me to follow these paths and have always been supportive and understanding, with helping and protecting hands. Thank you to everyone who has been a part of my journey.

Preface

This dissertation marks the culmination of my tenure as a Ph.D. candidate at the University of Southern Denmark and Leipzig University, guided by Prof. Stefan Jänicke. It encompasses eight scholarly articles, stemming from research conducted collaboratively within two distinct projects. Despite their varied scopes, these works collectively address the theme of *visualization of digital humanities and cultural heritage data and the interactive storytelling with those interactive depictions*.

The thesis is structured into six chapters, beginning with an **Introduction** (Chapter 1) that outlines the broad themes and key domains of digital humanities, cultural heritage, and visualization. This section also delves into the challenges and methodologies that permeate the research presented in this thesis.

Chapter 2 **Visualization-based Storytelling** gives an report of the state of the art and proposes a holistic design space to analyze storytelling with visualizations for digital humanities and cultural heritage in form of following paper:

1. J. Kusnick, N. Sindlev Andersen, J. Liem, E. Mayr, S. Beck, S. Koch, C. Doppler, K. Seirafi, S. Jänicke, and F. Windhager. "A Survey on Visualization-based Storytelling in Digital Humanities and Cultural Heritage". Submitted to the journal Visual Informatics. 2024

Chapter 3 **Musical Instruments and Musical Pieces** showcases the visualization and auralization of digital meta-information of musical instrument biographies and possibly related musical pieces. This chapter is based on two papers:

2. J. Kusnick, R. Khulusi, J. Focht, and S. Jänicke. "A Timeline Metaphor for Analyzing the Relationships between Musical Instruments and Musical Pieces." In: *VISIGRAPP (3: IVAPP)*. 2020, pp. 240–251
3. J. Kusnick, J. Focht, and S. Jänicke. "Visualizing the Aura of Musical Instruments". In: *Proceedings of 2nd EADH conference 'Interdisciplinary Perspectives on Data', 2021, Krasnoyarsk, Russia*. 2021

Chapter 4 **Sustainability of Materials used for Musical Instruments** sheds light on natural materials originating from plant and animal species used for the production of musical instruments. The visualization of (music) ecosystems throughout various zoom levels and their interconnectivity is meant for domain experts of related fields such as ecology and geography but also for a broader audience via storytelling in two papers:

4. J. Kusnick, S. Lichtenberg, D. Wiegreffe, E. Huber-Sannwald, U. Nehren, and S. Jänicke. "Visual Analysis of Diversity and Threat Status of Natural Materials for Musical Instruments". Submitted to the journal Frontiers in Environmental Science. 2024
5. J. Kusnick, S. Lichtenberg, and S. Jänicke. "Visualization-based Scrollytelling of Coupled Threats for Biodiversity, Species and Music Cultures". In: *Workshop on Visualisation in Environmental Sciences (EnvirVis)*. Ed. by S. Dutta, K. Feige, K. Rink, and D. Zeckzer. The Eurographics Association, 2023. ISBN: 978-3-03868-223-3. DOI: 10.2312/envirvis.20231112

Chapter 5 **Universal Approaches to Visualization-based Storytelling** proposes a holistic, systematic multi-practice workflow approach, including data curation, visual analysis and communication via storytelling for multi-visualizations of multi-entities in form of three papers:

6. E. Mayr, F. Windhager, J. Liem, S. Beck, S. Koch, J. Kusnick, and S. Jänicke. "The Multiple Faces of Cultural Heritage: Towards an Integrated Visualization Platform for Tangible and Intangible Cultural Assets". In: *2022 IEEE 7th Workshop on Visualization for the Digital Humanities (VIS4DH)*. 2022, pp. 13–18. DOI: 10.1109/VIS4DH57440.2022.00008

7. J. Liem, J. Kusnick, S. Beck, F. Windhager, and E. Mayr. "A Workflow Approach to Visualization-Based Storytelling with Cultural Heritage Data". In: *2023 IEEE 8th Workshop on Visualization for the Digital Humanities (VIS4DH)*. 2023, pp. 13–17. DOI: 10.1109/VIS4DH60378.2023.00008

8. J. Kusnick, E. Mayr, K. Seirafi, S. Beck, J. Liem, and F. Windhager. "Every Thing Can Be a Hero! Narrative Visualization of Person, Object, and Other Biographies". Submitted to the journal informatics. 2024

Chapter 6 **Overall Discussion and Summary** concludes with overarching observations and open challenges.

The listed papers have been mainly typeset to fit the format of the thesis. At the start of each chapter the following papers are introduced and their contributions summarized.

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During a panel discussion in 2020 at the Musical Instrument Museum in Leipzig, Germany where I presented a talk on the incompatibility of vocabularies, I became aware of the idea that I desired a comprehensive and holistic system for knowledge storage, data editing, visual analysis, and the capturing of corresponding findings and stories. A platform where data and visualizations are stored and can be commented on and annotated by experts from various domains.
These diverse stories, even if they might contradict each other, were something I only knew from developing fascinating and complex user scenarios for our systems at that time.
After I had intensively engaged with the construction and modification history of musical instruments for such an use case with the help of Sebastian, I met Silke during this series of talks. She spoke about similarly complex problems in regards to the sustainability of instrument making and convinced with a multi-layered timeline in which I saw a depiction of this multi-dimensional and multi-domain idea.
Only at the end of the work on my thesis did I realize that I had worked on this exact idea together with a whole, diverse team of experts from various domains and scientists ...

1 Introduction

As the title of my dissertation suggests, I will apply visualization-based storytelling to cultural heritage and digital humanities and explore its various aspects. To set the scene, I will briefly introduce the research areas digital humanities, cultural heritage, data visualizations and the interactive storytelling with those depictions in these areas. According to the nested model by Munzner to assess and design domain-specific visualization tools [313] this overview is structured along the *Domain Situation* (*What?*, see Section 1.1), narrowing down the domains digital humanities and cultural heritage by introducing into their focuses and goals. They are followed by the *Data/Task Abstraction* (*Why?*, see Section 1.2) in form of their data and concomitant tasks and challenges for visualizations as third and bridging domain. The last part, the *Visual Encoding/Interaction Idiom* (*How?*, see Section 1.3), specifically focus on storytelling as step towards solutions of the manifold challenges and mean of communication and outreach.

I want to lay out the different domains and concepts which are important within this interdisciplinary research, because these characteristics, challenges, and possible solutions are constant matter of design choices for approaches and prototypes during this journey.

1.1 Digital Humanities, Cultural Heritage and Visualizations

"Heritage is the result of a selection process.
It is not everything from our history -
heritage and history are not one and the same."
– William S. Logan [273]

The purpose of this section is to set the scene by expanding on the research areas and domains covered. In Munzner's methodology [313], this would be the domain situation, so the questions that arise are:
What *are we going to do and* ***which*** *domains are we going to dive into?*
What *are the tasks and* ***what*** *are the interesting entities within these domains?*
What *are we going to visualize and* ***what*** *visualizations might be feasible for that?*
Therefore, I will briefly introduce digital humanities and cultural heritage as well as visualizations in the following.

Digital Humanities

Digital Humanities (DH) represent an interdisciplinary field that intersects the use of computing tools and digital technologies with the disciplines of the humanities. This fusion aims to enhance, reimagine, and expand traditional humanities scholarship through digital means. The field encompasses a wide range of activities, including but not limited to digitization of archives, data analysis, visualization, the creation of digital collections, and the development of digital tools to analyze texts, artifacts, and cultural phenomena.
Detailed tasks of DH include:

Digitization and Archiving: Converting historical texts, artworks, and artifacts into digital formats to preserve them and make them more accessible.

Data Analysis: Employing statistical and computational methods to analyze large datasets of humanities content, such as textual or visual corpora, to uncover patterns or trends.

Visualization: Creating visual depictions of data and research findings to enhance comprehension and communication of complex ideas.

Development of Digital Tools: Designing software and applications tailored to the needs of humanities research, including text analysis tools, mapping software, and databases.

Digital Publication: Publishing research findings in digital formats that may include interactive components, multimedia, and links to underlying data.

Public Engagement: Utilizing digital platforms to disseminate research and engage with broader audiences, including scholars, educators, and the public.

The field of digital humanities is dynamic and evolving, continuously adapting to technological advancements and changing scholarly needs. As such, it represents a vibrant area of research that has the potential to transform the ways in which humanities scholarship is conducted and disseminated. But this complexity also means that this research field comes with certain challenges:

Technical Expertise: The interdisciplinary nature of digital humanities requires scholars to have both humanities insight and technical skills, which can be a significant learning curve.

Funding and Resources: Acquiring the necessary funding and resources for digital projects, especially for long-term sustainability and maintenance, is often challenging.

Data Management: Managing large datasets, ensuring their integrity, and addressing issues related to privacy and copyright can be complex.

Transdisciplinary Collaboration: Effective collaboration across different disciplines and skill sets is essential but can be difficult to facilitate because of for example different or even contradicting requirements or interests.

Digital Divide: The accessibility of digital humanities projects can be limited by the "digital divide" [351], affecting who can participate in and benefit from such research.

Scholarly Recognition: The recognition and valorization of digital humanities work within the traditional academic reward systems can be problematic, as such work often diverges from conventional scholarly outputs like books and articles.

Cultural Heritage

Cultural Heritage (CH) encompasses the legacy of physical artifacts and intangible attributes of a group or society that are inherited from past generations, maintained in the present, and bestowed for the benefit of future generations. This includes a wide array of forms, from tangible assets like monuments, landscapes, and artifacts, to intangible elements such as traditions, languages, and knowledge. The concept embodies a shared bond, our inheritance from the past, what we live with today, and what we pass on to future generations. It is a testament to the diversity of the human experience and a reflection of the world's cultural diversity. Even though it is worth to mention, that not all historical and cultural elements are part of the heritage since they are rather subject to constant selection and reinterpretation processes by societies [273, 382].
The tasks of cultural heritage resemble around:

Preservation: Protecting and maintaining cultural heritage in its original form as much as possible. This involves conserving physical structures and artifacts, as well as documenting and safeguarding intangible cultural expressions, including their digitized derivates handled as new (digital) artifacts.

Restoration: Undertaking actions to restore degraded, damaged, or otherwise altered elements of cultural heritage to their original state. Restoration work requires a deep understanding of historical context, materials, and techniques.

Documentation: Recording details about cultural heritage, including historical significance, current condition, and restoration efforts. Documentation can be in various forms, such as written records, photographs, and digital databases.

Education: Educating the public about the value and significance of cultural heritage. This includes developing educational programs, exhibitions, and materials that highlight the importance of preservation and the role of cultural heritage in society.

Research: Conducting research to uncover more about the history, significance, and context of cultural heritage objects and practices. This research helps in understanding, preserving, and interpreting cultural heritage.

Addressing these tasks requires a coordinated effort from governments, cultural organizations, communities, and international bodies. This involves not only investing in preservation and restoration but also in raising awareness about the importance of cultural heritage and fostering a sense of responsibility towards its protection facing following challenges:

Environmental Threats: Natural disasters, climate change, and pollution can cause irreversible damage to cultural heritage sites and artifacts.

Urbanization: Rapid urban development can lead to the destruction of historical sites and cultural landscapes, erasing links to the past.

War and Conflict: Conflicts can lead to the intentional destruction of cultural heritage as a strategy to undermine the cultural identity of opponents. Looting and trafficking of artifacts also increase during conflicts.

Neglect and Decay: Without proper care and investment, cultural heritage can fall into disrepair and decay [93], leading to the loss of historical and cultural information.

Globalization and Cultural Homogenization: The spread of a global culture can erode local cultures and traditions, leading to a loss of diversity in intangible cultural heritage.

Funding and Resources: Adequate funding and resources are often lacking for the conservation and restoration of cultural heritage, making it difficult to protect and maintain these invaluable assets.

Similarities between DH & CH

While DH and CH are outlined to have differences, they also possess significant commonalities in terms of goals, methods, and challenges.

Digitization and Accessibility: Both fields employ digitization to preserve artifacts, texts, and other cultural expressions, ensuring their longevity and reducing physical wear from handling. Through digital platforms and tools, these cultural and historical resources are made increasingly accessible to the global public, scholars, and educators, overcoming geographical and economic barriers to access.

Interdisciplinary Collaboration and Technology: DH and CH both thrive on interdisciplinary collaboration, bringing together experts in humanities, social sciences, library and information science, technology and other fields to address complex questions and projects. By doing so both fields integrate a range of digital technologies, such as data visualizations, renderings, Mixed Reality (XR), and Artificial Intelligence (AI), to create new ways of interacting with cultural and historical data.

Public Engagement: DH and CH projects often aim to engage the public through interactive exhibits, digital archives, and educational resources, but also literary publishing of research findings, fostering a deeper understanding and appreciation and interaction of the contents.

Data Analysis: Techniques such as text mining, data visualization, network analysis and machine learning are used in both fields to analyze cultural data, uncover patterns, and generate new insights into human culture and history while they facing similar methological challenges in regards to their analyzed data (see next chapter on *Why?* Section 1.2).

Sustainable Digital Preservation: The long-term preservation of digital assets and the development of sustainable practices are common concerns, including the challenges of data storage, format obsolescence, and maintaining access to and usability of digital collections and scholarly resources over time.

Entities within DH & CH Data

Thanks to the ongoing digitization within DH and CH corpora, collections and data bases are waiting for processing and further use in scientific, artistic and didactical approaches. The methodologies to do so are manifold and so are the challenges that are coming with the data. One of the main criteria involves the examination and modeling of "entities" within data sets and collections, a process that begins even during their digitization. I am introducing those different existing and in data modeled entities here since they will be constant matter of discussions in regards to designs of data, visual interfaces and elements and algorithms for the latter use within visualizations or storytelling. The entities that populate the DH and CH landscapes are incredibly diverse, encompassing both tangible and intangible elements:

Objects include physical objects and places such as buildings, monuments, statues, landscapes, archive materials, books, works of art, artifacts, and–since we are going to dive deeper into musicology–also musical instruments, musical compositions and their interplay in form of interpretations. Padilla advocates for viewing digital collections as data, emphasizing that all digital objects, including wax cylinders, reel to reel tape, vellum manuscripts, websites, and social media, should be seen as data amenable to computation [335]. He highlights the benefits of this perspective shift, notably how it broadens the scope of questions that can be asked about these objects. Many approaches encourage innovative uses of historic collections through digitization and metadata management, facilitating various types of computational analysis and highlights the transition of collections into a data-focused perspective [478]. By considering digital objects as computationally processable data, new ways of meaning-making are unlocked, leveraging unique data affordances, since they all have specific significances, own characteristcs and nowadays there are enough examples of purely digitally born (heritage) object [479]. This arouses questions about how underlying standards and structures of digital objects can be computationally analyzed to better understand the networks of meaning they are part of. One of the critical aspects to be highlighted in this context is the *provenance research*, which plays a pivotal role in understanding the origins and history of these entities, enriching our comprehension of their significance and context. Additionally, computational tools might be able in assessing artistic elements within artifacts, like hue, saturation, and style when visual art is viewed as data. This approach fosters a deeper understanding of digital objects beyond their surface representation, tapping into the vast potential of computational analysis. But "collections" or data repositories in DH and CH are consisting of more entities than only objects:

Persons are integral to DH and CH, connecting closely to the tangible and intangible artifacts they create or interact with, since most of these objects and tradition are often made by humans. These actors include in case of the cultural sector mainly artists, such as actors, painters, musicians, sculptors, architects, but also teachers, publisher, distributors, restorers, instrument makers. But next to artists in CH the persons of the humanities contains further groups such as politicians, researchers, scientists, religious figures. They also have the ability and tenancy to form various groups such as organizations, religions, or art schools. So that the analysis of persons scales from the research of individual biographies towards prosopographical analysis of groups and masses. Understanding their biographies and their connections and the networks among them enriches our grasp of historical and cultural contexts [31]. The insights into person's biographies tells us a lot about the circumstance of their times, creating a collective memory and revealing insights into society [17].

Events interlink the above listed entities through the documentation of interactions. Examples of those interactions are mostly "creational" such as creations of artifacts by their artists, founding of collections or the birth of children. But they also describe the transitions from certain states into others such as a painting getting restored or reworked into other artworks or actors move from one location to another or form an artistic movement or trend in collaboration with others. Pivotal as well are aggregated events, consisting of thousands of smaller events such as significant, world-wide spanning historical moments like conflicts or wars. These events not only mark the interactions among entities but also the transitions and movements within the cultural and historical tapestry they belong to.

Groups and Institutions include entities like collections, museums, orchestras, universities, projects, companies, and schools representing the organizational and collaborative aspects of cultural heritage and embodying collective efforts in the preservation, interpretation, and dissemination of heritage and humanities.

Culture and Nature as intangible aspects of heritage, including traditions, crafts, performances, and the practice of creating art itself (such as poetry or music), form a rich layer of human expression and social memory, deserving of preservation and study. The natural entities such as animals, plants, specific areas and ecosystems contribute to our understanding of the world's heritage, its (bio)diversity and highlighting the interconnectedness of human and natural histories. Unfortunately those intangible elements are rarely digitally modeled and available in databases. Instances of them are animals and plants as well as materials designed in a Korean collection [225], animals are highlighted as specially protected "objects" (in conflicts) [244], or UNESCO's collected list of intangible, including natural, cultural heritage [430], where the single elements are also visualized in relation to each other via a network graph. Hence the entities discussed are not isolated; they are interwoven through relationships and stories that emerge from their interactions.

In summary, the entities modeled and inspected within DH and CH data sets are foundational to the disciplines' methodologies and challenges. From tangible artifacts and digital objects to human figures, groups, and intangible cultural practices, these entities form a complex web of relationships that tell the rich stories of human history and cultural expression. Through the digitization and computational analysis of these entities, the fields of digital humanities and cultural heritage continue to expand our understanding and appreciation of the past, fostering a deeper connection to our collective cultural identity. Data Visualization serves as one of such crucial bridges, transforming abstract data and computational analyses into accessible, intuitive, and visually engaging narratives.

Visualizations

Visualization involves the art and science of crafting graphic or visual representations that are easy to communicate and understand. These visualizations transform large volumes of complex, both quantitative and qualitative, data into static, dynamic, or interactive visuals. Originating from specific fields of expertise, visual tools aim to make data accessible to a wide audience, enabling them to visually explore, quickly grasp, interpret, and uncover vital insights about intricate data patterns, relationships, trends, and anomalies.

Information visualization specifically focuses on depicting primarily quantitative data in a structured visual format. It employs various visual elements like tables, charts (for example bar, line, pie, and histograms), graphs, diagrams, plots (for example scatter and box plots), and maps (such as choropleth and heat maps), among others. Information visualization, however, extends to handling large, complex datasets comprising both quantitative and qualitative data. Its purpose is to enhance raw data's value, improving user understanding and decision-making through interaction with computer-supported graphical displays. This includes utilizing maps (e.g., tree maps), animations, infographics, diagrams (e.g., Sankey and flow charts), and various plotting tools (e.g., timelines and mind maps). These elements can be integrated into dashboards or multiple-linked views to enable a variety of comprehensive user practices with visualizations such as leisure, exploration, visual analytics, decision-support and the communication or presentation. Recent developments such as innovations in virtual, augmented, and mixed reality are pushing the boundaries of information visualization, making it more immersive, intuitive, and interactive and enhances users' visual engagement and cognitive processes. Unlike scientific visualization, which focuses on generating realistic images from physical and spatial data for hypothesis testing, data and information visualization aims to present and explore abstract, non-physical data from diverse sources like databases and documents for both exploratory and presentational purposes.

Inherently involved in the processes of transformations from data into visuals is the *data abstraction* in preparation of the further abstraction by *visual encoding* and *design*. Data abstraction in Tamara Munzner's model for Visualization Analysis & Design [314] refers to the process of identifying and defining the core data types and structures that are most relevant for visualization purposes. This abstraction process helps in the design of effective visual representations by focusing on the inherent properties of the data, such as its dimensionality, scale, and type (quantitative, ordinal, categorical), allowing for more informed decisions about visual encoding and interaction techniques. By abstracting data in this way, Munzner's framework aids in creating visualizations that are not only tailored to the data's nature but also to the analytical tasks and questions they are meant to support. That is why the characteristics of DH and CH (or applied domains in general), and their requirementes but challenges are influencing the the design of applied visualizations that much. This is also underlining that visualization as field here acts rather as "assisting" science for the applied domains. Therefore co-design and "participatory visualization design" processes are commonly used to involve the end users in the development of tools crafted for them and to gain help in understanding semantics and fulfillment of the data with meaning and live [111, 203].

Even though the details of the specific visualizations and general techniques are discussed throughout the following publications, I still want to give a short overview of common visual approaches towards the above listed characteristics and challenges. The focus on developments over time, and often historical contexts of content and data in DH and CH leads to a significant use of time-focused visualizations in form of **timelines**. Also in further visualizations the time is visually encoded to add temporal dimensions to them by various means such as color, juxtaposition, or animations to visually encode the chronology of events and their data points. But since actors, artifacts, and collections can be located throughout our world also **geospatial map**pings are common visualization approaches. The (hi)story of relevant entities then is often depicted as geospatial-temporal combination of **timelines and maps**. In addition to their geo-spatial and temporal correlation the relations between the various entities within DH and CH data sets and throughout them are also of high importance and **network graphs** are commonly used to visualized them, allowing network analysis and the visual detection of for example clusters. In general those constellations of multiple entities, such as groups, institutions or subsets of entities are also getting more tangible within set visualizations [5]. Those "major" visualizations are often accompanied by supporting **statistical charts** to give an overview or summary of aggregated or filtered data. Through rapid technical improvements the tools to digitize CH objects are becoming more approachable and achievable and are broadly used to create three-dimensional (3D) surface scans and the resulting three-dimensional models can then be use to make the artifacts more tangible by interactive **renderings**, enhanced by further visualization techniques such as augmented (AR) or virtual reality (VR).

In the realm of data visualization, scalability from individual entities to an aggregate view within a single visualization presents a unique challenge. To address this, **glyphs** and similar **visual metaphors** emerge as tools, aggregating data points and entities to offer both detailed and holistic perspectives. Glyphs, with their compact and expressive nature, serve as miniature representations, encapsulating complex data attributes in a visually digestible form. They can also enhance other visualizations, such as depicting point clusters on geospatial maps. Similarly, semantic zooms play a crucial role, allowing users to seamlessly transition between detailed and aggregated views. This dynamic scaling is not merely a feature but a necessity, enabling close and distant reading—or viewing—of data. Furthermore in our era, where mobile devices are ubiquitous, the design of visualizations also needs to be responsive, ensuring accessibility and functionality across a range of devices, using such aggregation and simplification methods to be feasible on smaller and touch controlled screens.

However, the journey of visualization carries its own set of challenges and dangers, particularly the risk of distorting the viewer's perception of data for example by simplification. We will later see that accompanying storytelling can be an effective strategy to mitigate this, providing context and narrative that guide the interpretation of visualized information, but also their prior data, abstraction and transformation.

It is worth to mention here that such visualization strategies and their evolving tools are not intended to produce definitive results on their own. Instead, they are crafted as tools to assist domain experts in analyzing and communicating their data in novel ways. Emphasizing a "human in the loop" approach, these visualizations are designed to provoke questions and encourage further research, acting as catalysts for exploration rather than endpoints of analysis.

The development process itself is deeply participatory, characterized by iterative exchanges and co-development between designers, researchers, and end-users. This collaborative approach not only fosters innovation but also ensures that the resulting visualizations are deeply aligned with the users' needs and contexts. Ongoing iterations within the non-linear design and developing processes are crucial, sparking new questions and insights at every stage, continuously refining and enhancing the tools. Yes, this also means that often external domain experience is needed to untangle the bound and implicit knowledge which lies in the meaning and interpretation of (visualized) data points and patterns. Those sense-making stories often stay hidden or they are only documented by use cases in according publications. On the other hand those use cases play an important role to illustrate the efficacy and application of these visualization tools to the various scientific communities and audiences. By showcasing real-world examples of how domain experts and end-users interact with the prototypes, these use cases provide tangible insights into the impact and utility of the visualizations. Through this iterative, participatory process, visualization design evolves as a field, bridging the gap between complex data and human understanding, and enriching the dialogue between researchers and the data they seek to explore [203].

1.2 Challenges in Digital Humanities and Cultural Heritage

"History is written by the Victors." – Winston Churchill

Particularly because of their similar tasks and characteristics, digital humanities (DH) and cultural heritage (CH) face a unique set of challenges in terms of digitisation, the resulting data and datasets, and the implications for scholarly work and public interpretation. In Munzner's nested model, the next level is the "data & task abstraction" [313], which touches on issues such as:
Why *are we looking at visualisation and storytelling for these application domains?*
Why *are practitioners using the resulting tools?*
Why *do we design the visual elements, interfaces and visualizations this way?*
In order to justify this, it is helpful to highlight the domain-specific characteristics and challenges, especially with regard to the digitized information. So I have collected the following common challenges, including:

Historical Contexts: DH and CH often utilize a perspective towards the past resulting in bygone data sets throughout the centuries. This is accompanied by a wide variety of changing historical contexts which have to taken into account during digitization, analysis and processing of information and artifacts. This also holds true for the interpretation of contents or meta information since conventions and receptions also developed. But also descriptive vocabulary such as names, concepts, borders or their meanings changed over time, so that they call for clarification and translation.

Complex Contents: Due to their deep inter-linkage with society, cultural and humanities disciplines are working on complex problems, concepts or systems of various "zoom" levels and their inter-dependencies. Resulting from that available information are highly complex, scattered, incomplete so that contents needs sophisticated and intellectual processing and controls. This is aggravated by (historical) uncertainties and subjectivity in case of for example contested (historical) contents and narratives. The data can be handled and processed at scale but the interpretation of it becomes challenging because of missed nuances, context, and the interpretive depth that traditional humanities scholarship values.

Digital Research Bias: The phenomenon specifically relating to DH and CH, focusing on the disproportionate research and dating of popular entities versus the neglect of the majority could be described as "digital research bias" or "cultural data neglect". It is a complex issue stemming from factors such as availability of data, research funding, public interest, and the inherent bias towards well-known or well-preserved artifacts and historical periods and institutional prejudices. The issue reflects broader discussions on the priorities, methodologies, and biases present in the digitization and study of cultural and historical data. The effects might be manifold so that it is challenging to ensure that all communities or phenomena are equally researched, digitized or represented, leading to biases in approaches, findings and results.

Preservation and Digitization: Historical and cultural artifacts are often facing a variety of risks and threats. These risks encompass environmental threats such as earthquakes, flooding, and fires, or even inadequate room climate, as well as human-made dangers like theft, conflicts, and vandalism. Consequently, there is often a need to evaluate these risks and threats, while also implementing measures to safeguard DH and CH artifacts [352]. One of the methods to preserve is the digitization of these artifacts but due to the historically variable precision in documentation and the limited availability of information, datasets in DH and CH may be incomplete, inaccurate, or inconsistent, potentially affecting research outcomes. Consequently, ensuring data quality and the process of data cleaning demand significant time and expertise. Digitizing both tangible and intangible CH is a labor-intensive task that requires specialized equipment and expertise. Achieving high-quality digital reproductions that faithfully represent the original artifacts or expressions presents a notable challenge. The transition from analog to digital formats during digitization inherently leads to rasterization, and consequently, a loss in precision. Additionally, distortions of the digital artifacts can occur due to format transformations or compression. For these reasons, documenting the choices made in data selection, preparation, and analysis is essential for ensuring reproducibility and maintaining scholarly integrity. However, articulating complex methodological decisions can be challenging.

Bridging Silos: In the realms of DH and CH, the promise of interoperable data opens up unprecedented opportunities for research, preservation, and dissemination. However, realizing this potential is hampered by significant challenges, paramount among them being the difficulty of combining datasets. This challenge arises from the diverse data formats and vocabularies in use, underscoring the pressing need for standards and ontologies. Such standards not only facilitate the harmonization of data but also enhance the accessibility and utility of invaluable cultural and historical resources. Yet, the path to interoperability is fraught with technical hurdles. Transformations between different formats and vocabularies can be technically daunting, complicating comprehensive approaches to analysis and interpretation. This situation is exacerbated by the lack of standardized formats and protocols specifically tailored for DH and CH data, leading to data silos, databases which might be homogenized but not connectable to others. The absence of these standards severely impacts the interoperability between various databases and systems, creating barriers to data sharing and integration across platforms and institutions. The consequences of these challenges are far-reaching. They contribute to a landscape where data can become elitary, accessible only to those with the resources and expertise to navigate these complexities. Furthermore, the current state of affairs often leads to overlap and duplicates in data collections, wasting valuable resources and effort. Perhaps most troubling is the emergence of contradictory information, which can undermine the integrity of research and analysis. Addressing these issues requires a concerted effort to develop and adopt shared standards and ontologies that cater to the unique needs of the DH and CH sectors. By doing so, we can unlock the full potential of digital data, transforming it into a powerful tool for understanding and preserving the rich tapestry of human culture and history.

Data Uncertainties: Digital datasets related to CH and DH research often encompass historical time periods and geographic locations. However, the temporal and spatial metadata associated with these datasets can be uncertain or ambiguous, complicating efforts to accurately place data within its historical and geographic context [199, 224]. Those uncertainties need to be addressed and communicated transparently throughout the procedures of further processing, analysis and visualizations. To support that creating detailed metadata (data about data) is crucial for cultural heritage datasets to be useful. This includes provenance, historical context, conservation status, and more. However, generating comprehensive and standardized metadata is a time-consuming process that often faces inconsistencies.

Vastness and Sparsity: Especially with the advent of high-resolution imaging and 3D scanning technologies, data sets in DH and CH where growing intensively. The sheer volume of digitized information can be overwhelming, requiring substantial computational resources and expertise to store, manage, and analyze effectively. On the other hand, the already mentioned digital research bias or "skewness" leads to a sparsity and shortcoming of available (meta) information, especially when it comes to CH objects [224]. Furthermore, connections between the various entities within but also throughout the data sets are often missing, making it challenging to depict biographies and complex matters without additional data or expert knowledge.

Sensitivity and Rights: Accessing relevant and usable digitized data can be a challenging task, particularly for materials that are rare, under copyright protection, or yet to be digitized. The legal constraints on copyrighted materials further complicate the landscape, restricting access and use of digital resources and thereby affecting the development and dissemination of research projects. Professionals in the DH and CH sectors are also deeply engaged in navigating the ethical issues surrounding the digital representation and use of culturally sensitive materials. These issues encompass concerns over consent, privacy, and the risk of misinterpretation or misuse. Moreover, DH and CH experts frequently face legal hurdles related to copyright, fair use, and the digitization of protected materials, which requires a nuanced understanding of a complex array of laws and regulations. Ethical dilemmas also emerge when handling sensitive data or information about individuals, necessitating a thoughtful approach to privacy, consent, and the avoidance of harm. This is especially true for the cultural expressions of indigenous and local communities, within CH datasets, calling for intricate legal and ethical considerations concerning copyright, ownership, and privacy. Successfully navigating these challenges to ensure respectful and lawful data use represents a significant hurdle, underscoring the need for careful and considerate engagement with both the legal and ethical dimensions of DH and CH work.

Representation and Sustainability: Ensuring the long-term preservation and accessibility of digital projects and data is critical, especially as technology evolves. The challenge extends to making these resources accessible and usable for a wide audience, including researchers, educators, and the general public. Digital preservation faces obstacles such as the durability of formats, media degradation, and technological obsolescence, necessitating ongoing effort and resources. Moreover, access involves not only technical aspects but also considerations of language, usability, and inclusivity, ensuring content is represented accurately to avoid misinterpretation or misappropriation. The aim is to maintain the integrity and accessibility of digital collections, making them meaningful and available to a broad audience.

Addressing these challenges requires multidisciplinary approaches, drawing on expertise in humanities, cultural heritage, computer science, library and information science, and legal and ethical studies, among others. Despite these challenges, the opportunities presented by DH and CH to uncover new insights, reach wider audiences, and engage with complex cultural phenomena in innovative ways are immense. But these potentials are not coming without further burdens not related to the data itself:

Funding and Engagement: Adequate funding and resources are necessary for digitization projects, maintaining digital archives, and developing technological solutions. However, cultural heritage and research institutions often face budget constraints that limit their capabilities in these areas. Additionally, often the documentation and communication of the processes within project are not planned or funded, so that the engagement of and the (scientific) communication for a broader audience becomes challenging and the interesting stories remain hidden. Furthermore, encouraging active engagement and participation from communities, especially in the documentation and interpretation of intangible cultural heritage, requires building trust and developing collaborative approaches. But also the integration of and fit for needs and requirements for experts of adjacent domains are difficult to assess and implement in detail.

A step towards solutions to these challenges and a method of bridging these differences and gaps across various domains is through holistic approaches to the complex problems faced, employing polyvalent visualization and storytelling as a means of memorable and understandable communication.

1.3 Storytelling with Visualizations

"When we get to the end of the story,
you will know more than you do now..."
– Hans Christian Andersen, The Snow Queen

In order to meet the challenges mentioned above and to gain holistic and instructive insights into the diverse world of digital humanities and cultural heritage by means of visual analysis and to present them in the best possible way, we are now dealing with the storyteller and the use of interactive visualizations in this context.

As last stage before the actual implementation–the "algorithm"–of visual tools, Munzner proposes the design of the "visual encoding and interaction idiom" [313], leading to questions such as:
How *are we going to approach to overcome the discussed domain challenges?*
How *are we implementing storytelling methods into the visualizations?*
How *are we designing visual elements and interactions to fulfill our undertakings?*

When we as humans try to convey information in an impressive and memorable way via any communication channel we often (consciously and unconsciously) do this by telling our story of it. We implicitly use storytelling techniques to make this knowledge dissemination as remarkable as possible. We build up tension throughout our story to increase the attention and engagement of our story listener, just to release all the tension at the end of our story to underline the point we want to make or the information we want to convey. Or we use story hooks in the beginning to attract and bound the listeners attention by for example *for-shadowing* or *in medias res* techniques.

The interface of digital humanities, cultural heritage, visualizations and the storytelling with visualizations marks an exciting frontier. From the dawn of human civilization, storytelling has served as a cornerstone of cultural transmission and knowledge dissemination. Despite the seismic shifts brought about by advancements in media and technology, the enduring power of narratives remains undiminished. Instead these new channels allow for a manifold of opportunities rich in accessibility and immersion.

Within our currently wide-ranging digitized and data-driven world the meaning and delicate understandings of historical and cultural contexts are in danger of getting forgotten. Often confined to the realm of visually appealing charts and graphs, data storytelling goes beyond mere visualization. It is a structured approach to communicating insights that weaves data, visuals and narrative into a cohesive understanding.

Storytelling–intangible cultural tradition itself–offers in combination with visualizations pathways towards the important and responsible preservation and dissemination of the richness of irreplaceable heritage and human history. Data storytelling is emerging as a transformative tool that infuses scientific inquiry with humanistic narrative to bring cultural artifacts to life. By combining technology and storytelling, we enable digital humanities and cultural heritage to transcend time and space, fostering engagement and dialogue among diverse audiences.

This leads to questions such as *Who is going to tell stories? Are these the domain experts or end users?* and *Who is going to be the hero? The encountered entities such as persons, objects, collections, groups or locations*?

Aslan writes *"Cultural heritage tells the stories of the world's many peoples."* [18], meaning that the heritage in itself informs about our societies and their ideas throughout history. Hence, Niccolucci, Felicetti, and Hermon describe a "Heritage Story" as the collective (documented or interpreted) information available on the heritage artifact and that this information should be presented in the most attractive manner possible [323]. On the other hand Pilgrim, curator of the Jim Crow Museum writes that there are "some" who are "labeling" and telling the stories of "others" [344], so that selected people decide for others on the ways to interpret history and heritage, leaving us with questions on elitism and rhetoric.

When it comes to the abstraction of elements from stories to visuals, the consideration of event sequences and their narrations (or stories) gets important and I want to highlight the difference between them here. The plot–the events of a (hi)story–is always ordered in a linear, chronological sequence but the narration doesn't necessarily has to follow this thread [133]. Instead the narration, thus the order of told and revisited events, is defined by the narrator–the creator–of the story.

These observations underline the fact that authors of stories have the power to select, interpret and present the information used according to their judgements and ideas, also including the risk of misuse. Visualization-based storytelling (VBS)–or interactive storytelling in general–with its user-involvement via options allows users to become authors or at least influence the narrative thread.

Within the visualizations interactions such as highlighting, filtering and brushing–the marking of elements throughout different views–of data points can be used to underline the "characters" and the visual storytelling techniques such as the juxtaposition, transitions, or animations are used to tell the varying circumstances during the progression throughout the story thread. VBS as such can be used as an introduction into complex topics but also comprehensive visualization systems, since the story can introduce into data, transformation and visual encoding as well as potentially nested aggregations and guide through advanced interactions or use cases [253].

Meuschke et al. underline in their approach to storytelling of disease stories, that VBS relays on the major key elements: *characters, conflict, content, and structure* [303] opening up a design space for storytelling. Resulting from this various narrative arcs exist such as plot-driven stories like *Freytag's pyramid* or character-driven stories such as Campbell's *Hero's Journey* [61] (for details see 2.2.5). The focus on characters as protagonists encountering the antagonists' challenges creates the opportunity to evoke emotions and make the stories personal. They create space for projections, so that the listeners (or viewers) can identify themselves with and project a manifold of emotions onto the characters. Through the characters in stories, we as humans can experience extraordinary situations without being exposed to any danger or suffering, holding the potential of learning from this simulated situation [76]. Since ancient times stories were told to pass on experiences and wisdom to further generations. Cron states that survivors (fittest, in the sense of survival-of-the-fittest) have been the people who have heard and understood the story on how to kill or survive the (animal) predators or any other threats [76]. The wall paintings within the caves have been visual expressions of those stories [72]. In the context of DH and CH, the question could be whether the continuous telling of stories, better called "the transmission to following generations" preserves our communities, traditions and knowledge.

In summary, in this thesis, I embark on a journey to explore the convergence of visualization-based storytelling with digital humanities and cultural heritage. By delving into the nuanced interplay between data science, visualizations and narrative discourse, I seek to illuminate the transformative potential of storytelling in the preservation, interpretation and dissemination of our collective heritage. Through interdisciplinary research and innovative methodologies, I aim to contribute to a deeper understanding of how storytelling can serve as a catalyst for cultural revitalization in the digital age.

2 Visualization-based Storytelling

"My father used to say that stories are
part of the most precious heritage of mankind."
– Tahir Shah, Arabian Nights: A Caravan of Moroccan Dreams

2.1 Overview & Contributions

In the rapidly evolving landscape of communication, digital, visual and visualization-based storytelling using data emerges as a powerful conduit for conveying complex commercial, journalistic or scientific ideas to a broad audience.

This chapter delves into the heart of visualization-based storytelling (VBS), exploring its unique ability to bridge the gap between intricate scientific concepts and their comprehension by diverse audiences. Through a blend of digital media, including interactive graphics, video, and virtual reality, storytellers can craft engaging narratives that resonate on a personal level, transforming abstract data into tangible experiences for manifold assets and concepts in digital humanities (DH) and cultural heritage (CH).

The essence of this storytelling approach lies in its capacity to humanize science, presenting facts and figures within compelling narratives that evoke emotion and foster a deeper connection with the content. By leveraging the visual medium, scientists and educators can illuminate the intricacies of their work, making it accessible and relatable to people outside their field. The chapter is based on Paper 1: **A Survey on Visualization-based Storytelling in Digital Humanities and Cultural Heritage** [256] and will therefore give an introduction into storytelling, an overview over related surveys and guide through the principles of VBS. This is done by introducing defining key features of VBS, which are then going to be used throughout the whole thesis to assess and discuss systems and their characteristics and their facets.

The article delves into the impact of digitization in arts and culture, generating vast data collections that offer new opportunities for storytelling, especially through VBS. This approach is identified as a potent means to communicate knowledge visually and narratively, facilitating the understanding of complex topics for diverse audiences.

By developing a VBS specific design space with a special focus on DH and CH topics, the survey maps out emerging areas and future research directions. This design space is intended to help scholars find suitable solutions for conveying topics through VBS, advancing the field through collective efforts to address open challenges. Furthermore the survey presents an overview of the current state of the art of VBS tools and examples in the realms of DH and CH showcasing examples where these techniques have been effectively applied in scientific and public communication. It will explore the tools and strategies for creating impactful stories, discuss the challenges and opportunities inherent in this approach.

Ultimately the survey also sheds light on open and future challenges, offering insights into the future of storytelling in the digital age and as motivation of following research and our developments explained within this thesis. As the journey through the digital landscape continues, it will be discovered how VBS not only enhances public engagement with science but also encourages a multidisciplinary approach to research dissemination.

The main contributions of the article can be summarized as follows:

1. **Comprehensive Overview of VBS in DH and CH:** We provide a detailed examination of 34 unique VBS designs, aiming to present contemporary trends and best practices in the field. This selection underscores the diversity within VBS examples and highlights emergent trends and gaps that can inform foundational principles and creative possibilities for VBS.

2. **Categorization and Analysis of VBS Examples:** By categorizing VBS examples based on their main visualization types and storytelling aspects, we identify dominant approaches and innovative practices. This analysis reveals a preference for simplicity and accessibility in VBS designs, with a strong reliance on textual narratives and linear story structures.

3. **Identification of High-Level Themes:** Several high-level themes emerge from the analysis, including *Narrative Structure*, *Causality & Messaging*, *Identification & Familarity*, *Involvement & Engagement*, *Emotion & Affection*, and the exploration of innovative and experimental approaches. These themes contribute to understanding the current landscape of VBS in DH and CH and point to areas for further research and development.

4. **Comprehensive Design Space for VBS in DH & CH:** Consisting of two main parts – *VBS Means* and *VBS Presentation* – with their respective dimensions we are proposing a design space to create and describe VBS tools and examples (see Figure 2.2). Whereby the *VBS Means* consist of general VBS characteristics, applicable to story examples and authoring tools, such as the used visualization and media types and their possible linkage. On the other hand the *VBS Presentation* is defining concrete realizations of stories analyzing which entity class is focused and how complex or which story pattern the story thread is following.

5. **Highlighted VBS Examples:** Specific VBS examples are discussed to illustrate how they embody the identified themes and design dimensions. This practical context helps bridge theoretical considerations with real-world applications, providing insights into how VBS can enhance the efficacy of storytelling in conveying informative, engaging, and immersive narratives.

6. **Future Challenges and Opportunities:** The survey outlines several open challenges and future directions for VBS in DH and CH. These include the exploration of mixed reality designs, storytelling with micro-content and gamification, the utilization of set and graph visualizations, balancing reader- and author-driven designs, addressing the lack of object-oriented storytelling, distinguishing between guidance, exploration, and storytelling, fostering critical reflection and avoiding oversimplification, and considering visualization and

storytelling rhetorics. These challenges highlight areas where VBS can evolve to better serve DH and CH objectives.

Overall, the article contributes to the field by offering a nuanced analysis of VBS examples, identifying key themes and gaps, and outlining future challenges that can guide the development of VBS practices in DH and CH.

2.2 Paper 1: A Survey on Visualization-based Storytelling in Digital Humanities and Cultural Heritage

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Abstract: *Storytelling is an engaging and effective way to design and communicate information as causally connected sequence of events. As shareable and memorable carriers of information, stories have been told throughout history and related techniques of storytelling have been constantly modernized and updated for changing media environments. As such, storytelling is omnipresent in modern-day society to communicate information in a multimodal fashion, including accounts on diverse fields of human culture. Reflecting on this transdisciplinary area of practice, this paper investigates visualization-based storytelling (VBS) techniques in digital humanities (DH) and cultural heritage (CH) domains. It analyzes the prior art in this field with regard to VBS tools and exemplary story designs to document best practices and map out future challenges. In doing so, we contribute to the fields of VBS, DH and CH in several ways: (i) We combine and enhance storytelling design spaces from related fields into a new comprehensive design space tailored to VBS in DH and CH fields. (ii) We describe and discuss best-practice solutions from related work and categorize them according to our design space criteria, making it possible to identify gaps and discuss open challenges. (iii) Lastly, we highlight the potential of technological and conceptual extensions for VBS in this field, such as augmented reality solutions, gamification and storytelling with micro-content. Ultimately, the outcome of this work is intended to consolidate an emergent area of visual and narrative practice and to provide a source collection for visualization, CH, and DH researchers to inform and strengthen collaborative research on advanced VBS solutions.*

2.2.1 Introduction

Storytelling is one of the oldest human practices to communicate and share the history of events engagingly and memorably. A joint characteristic of stories is the existence of a narrative thread, causally connecting persons, objects, places, or combinations of them and their changing properties and circumstances over time, as defined by [427]. Throughout history, stories have been told and recounted through oral or written traditions and depicted through visual arts, such as paintings on rock walls [38]. In modern times, stories have widely transcended the local use around fireplaces and evolved into universal expressions and vessels for complex information that are continually adapted to changing media landscapes [152].

Processes of digitization in arts, culture, and humanities domains have generated an abundance of data that waits to be processed, re-interpreted, and utilized in related practice and knowledge fields. For these rich and complex data collections which are studied across digital humanities and cultural heritage domains, *visualizations* can provide effective overviews, and make patterns, distributions, and relationships visible to scholars, expert users, and non-expert audiences.

What is essential for the following reflections is the fact that visualization techniques also provide the means to tell meaningful and remarkable stories—and to enhance the narrative bandwidth for conveying information significantly. The combined format of *visualization-based storytelling (VBS)* thus offers a simple yet powerful way of communicating knowledge visually and narratively [258], which also made it a ubiquitous topic in visualization research in recent years [363, 391]. On the application side, it has led to the development of different software tools for authoring VBS (see Subsection 2.2.6) and to an impressive variety of specific designs for communicating complex topics to a wide range of audiences (see Subsection 2.2.5).

Drawing upon current research and development in this area, we conduct a state-of-the-art survey focusing on the intersection of visualization-based storytelling with the digital humanities (DH) and cultural heritage (CH) fields. The main contribution of the survey is thus to succinctly conceptualize and consolidate the current state of VBS in DH and CH domains, which has not been systematically discussed by either side until now. By doing so, we devise a VBS design space with a particular conceptual orientation towards DH and CH topics, and thus with a unique applicability and relevance for VBS strategies in these domains. As a result, we map out emerging areas of VBS development, along with directions and challenges for future research in these growing fields. This will help future DH, CH and visualization scholars to find suitable solutions for conveying their topics through VBS—and to collectively advance the state of the art in all adjacent fields with responses to open challenges.

Subsection 2.2.2 summarizes related work and elaborates on the relevance of VBS with regard to key concepts. We define the scope of this survey in Subsection 2.2.3 and reflect on our guiding survey methodology in Subsection 2.2.4. In the following, we assemble a topic-centered design space for VBS in DH and CH fields in Subsection 2.2.5 and illustrate our central categories with state-of-the-art examples. Based on these categories, we analyze VBS tools in Subsection 2.2.6, which are available for CH and DH scholars and practitioners without a visualization or programming background. In addition, Subsection 2.2.7 reflects on findings for bespoke story designs developed by VBS research and practice. Finally, we discuss unique development challenges at the intersections of VBS with DH and CH data and topics in Subsection 2.2.8 with the aim to stimulate new research on all sides.

2.2.2 Visualization-Based Storytelling

It is evident, from their omnipresence in human culture and many academic reflections, that stories or narratives are wildly successful design strategies for conveying novel, relevant, or entertaining information both throughout human history but also in present-day culture [38, 105]. Multiple hypotheses have been proposed for why this is the case, including theories on a specific mode of narrative information processing in human cognition (e.g., [191]). Given this evolutionary success, also designers of "new media" are well-advised to know about—and where applicable make use of—the powers of narrative design. In discussing DH and CH, it's crucial to highlight the distinction between historical events and their narration. Given the more narrow focus of this survey on visualization-based storytelling, a schematic juxtaposition helps to sketch out why the combination of narrative and visual information design is of specific interest (see Figure 2.1). Shortly put, visualizations and narrations operate on opposing but complementary design principles [391, 404]: Stories aggregate and interweave information units sequentially as determined by an author

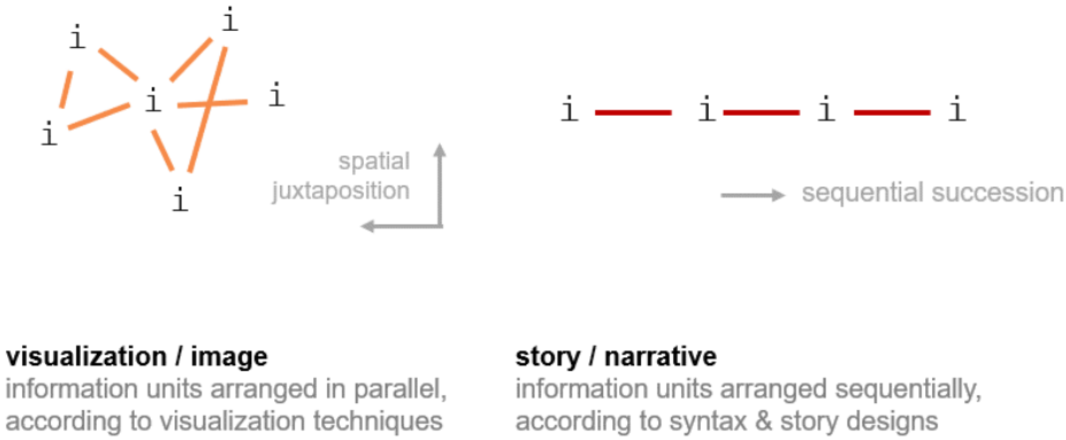

Figure 2.1: VBS combines two fundamental strategies to connect information units to complex aggregates: visualizations are based on the spatial juxtaposition of elements (left), whereas stories connect their information units sequentially (right).

(i.e., author-driven reception pathways), while visualizations are aggregates of information units that are juxtaposed at the same time—and readers must figure out how to navigate these open arrangements (reader-driven reception) regarding perception pathways and interaction methods [459]. A significant factor behind VBS's popularity in recent times has been the ability of digital devices and interfaces to integrate both design strategies (i.e., visualization and storytelling) with their complementary strengths. As such, VBS interweaves overviews for massive datasets with sequential guidance and narrative engagement in flexible combinations.

This first structural sketch of the complementary operating principles of stories and visualizations is corroborated by various definitions, including Ma, Liao, Frazier, Hauser, and Kostis [281], who argue that VBS is a viable approach to communicating complex scientific findings, as they increase comprehensibility, credibility, and involvement, especially when some form of interaction is included. In this context, they consider stories to consist of sequential accounts on causally related events over time that create lasting impressions and capture our attention. There have been similar definitions provided by Cruz and Machado [77], Kosara [243], Lee, Riche, Isenberg, and Carpendale [262], or Riche, Hurter, Diakopoulos, and Carpendale [363].

However, as VBS has gotten more popular, many voices in the visualization field pointed out the need to define and discuss the meaning and means of "stories" or "storytelling" more thoroughly [95, 120, 388, 404], especially in face of simplified assumptions that all visualizations are or tell stories themselves. On that matter, Denil [95] argues that storytelling goes beyond a visualization's (e.g. a map's) inherent ability to foster, influence, or reinforce a narrative. Regarding a related assumption, Few [120] warns "Data don't tell stories, people do". However, the number of contributions—which have been sparked by such calls for more conceptual rigor—have not simplified the overall discourse, as they have also generated competing technical terms for the shared topic of interest: Suggestions range from "narrative visualizations" to "data-driven stories", and from "visual data stories" to "storytelling in visualization". As such, we suggest to read the term of *visualization-based storytelling* as an inclusive concept in the context of this survey, which aims to interconnect many existing definitions—and even more so many related key concepts, which help to explain the relevance of storytelling.

Key Concepts

Narrative Structure: By definition, stories guide a recipient sequentially through a topic and related visualizations. The basic meaningful elements of stories—what we have called 'information units' in Figure 2.1—has also been termed 'states' [180, 375], 'story nodes' [281, 466], 'story pieces' [262], or 'plot points' [281], which are connected causally through a series of transitions. The specific aggregate or narrative 'gestalt' that builds up from these sequential chains is frequently referred to as the *plot* of a story [281]. In line with theories since antiquity, Few [120] argues that such plots are further structured by larger sequential units, including (at least) a "beginning, a middle, and an end". Such components typically build the classical three or five-act dramatic arcs of stories, including fundamentals like exposition (setting and conflict), rising action, climax, falling action, and resolution [470]. The narrative structure can also be supported through a meaningful layout [23], and by using navigational aids such as scrolling or slideshows [296]. With such a system of guidance VBS offers possibilities to "help the audience to better comprehend difficult or complex concepts" [105] by presenting information in stories, which might be beneficial in domains such as DH and CH where contexts stay intricate and might be effected by uncertainties, contested histories or pluri-vocal narration.

Causality & Messaging: A narrative sequence, not necessarily chronologically ordered, together with explanations, helps to express causal relations between the information units of a story [103, 180]. Emphasizing and highlighting changes between different system or story states is not only an important purpose of storytelling, but can also be one of visualizations. For concise and effective communication, Dykes [105] recommends focusing on a central point in a data story to emphasize a main message, insight, or argument. An argument, communicated through explanations, observations, and commentary [391], can be in a factual or narrated form [21]. The interpretation of such a message, however, is influenced by the author's experience and identity, similar to the impact a reader's culture, individual experiences, and perception have [179, 370]. While verbal techniques may be best suited to convey a message, nonverbal or visual elements can also convey and emphasize a data story's message [374]. So a clear illustration of cause-and-effect relationships can help convey the underlying messages of the data story more effectively. This involves structuring the narrative to show how historical events, cultural shifts, or specific actions led to particular outcomes, aided by the e.g. before-and-after comparisons via flowcharts or graphs.

Identification & Familiarity: Dykes [105] recommends to identify a story's heroes, giving them an identity and voice, and portraying their journey. Showing a story's hero(es)—e.g., the humans or valuable objects behind the data—helps to "make abstract data more relatable, and possibly establish an emotional connection between the viewer and the fate of the entities" [363]. (Visual) anchors or hooks, providing entry points the audience can identify with, are a way to create a familiar setting, direct attention to the key message, convey a first impression, stimulate default views to orient the audience, and to "paint the picture" [141, 179, 363, 391]. So building a sense of identification and familiarity can be achieved by relating the content to the viewer's own experiences or cultural background to create entry points for a broad range of audiences from the various sub-domains of CH and DH. This could involve showcasing common cultural elements, drawing parallels between past and present, or using familiar storytelling formats and archetypes.

Involvement & Engagement: Storytelling is a promising communication approach as humans acquire a narrative mode of thinking early in their development [54], which focuses on meaningful human intentions and actions over time rather than the analysis of facts and truth. They increase our attention and open us to new information [105]. Stories can deeply engage recipients ("narrative engagement", cp. [60]) in the flow of history and lead to a rewarding, entertaining, and joyful experience. Such positive experiences can also trigger further interaction with the information and are, therefore, also an indicator of successful visualization-based stories [296]. Actively involving participants in a data-driven story (e.g., by prompting estimation questions) can assist memory and ease comprehension of complex, abstract or historical DH and CH complexes and make them more tangible [363].

Emotion & Affection: Stories can evoke or reinforce emotional reactions (e.g., empathetic, cheerful, surprised, unpleasant, uncertain, or angry emotional states). Herman, Jahn, and Ryan [171] summarizes that "understanding narrative, just like understanding in general, is never purely cognitive. It is one of the major attractions of narratives [...] that they elicit emotional responses in their audiences.". Visualization-based stories can be emotional and sensory experiences and can evoke affective responses [327]. Schwabish [388] identifies emotion together with a meaningful climax as the two essential characteristics of a story. This means that viewers can develop a deeper connection with the history and culture being presented. This emotional connection can be particularly powerful in preserving intangible CH, such as traditions, languages, and practices. But this is also useful in DH, where the objective is often to explore the human aspects of history and culture. Emotions can provide a more nuanced view of historical events, societal changes, and cultural phenomena.

Related Surveys

Several articles related to our work have already analyzed and classified the growing field of visualizations used for data-driven storytelling—each with a specific focus that contributes to the development and understanding of VBS. We analyze the categorization schemes used in these surveys for a more holistic understanding of relevant design factors for VBS. Segel and Heer [391], for example, created a design space and suggested practices mainly for journalistic reappraisals of data into visual stories. Their classification is based on three main criteria: genre (main visualization technique), visual narrative tactics (visual structuring, highlighting, and transition guidance), and narrative structure tactics (ordering, interactivity, and messaging). Tong, Roberts, Borgo, Walton, Laramee, Wegba, Lu, Wang, Qu, Luo, et al. [427] review the use of storytelling in data visualization in general and present a broad range of common visual storytelling elements. They analyze mainly scientific publications along the questions and corresponding characteristics: who? (authoring-tools, user-engagement), how? (narratives, transitions) and why? (memorability, interpretation). As a second classification layer, they review the path through the sequence of events (linear, user-directed path, parallel, and random) as an adaptation of Segel and Heer's classification. Concern-

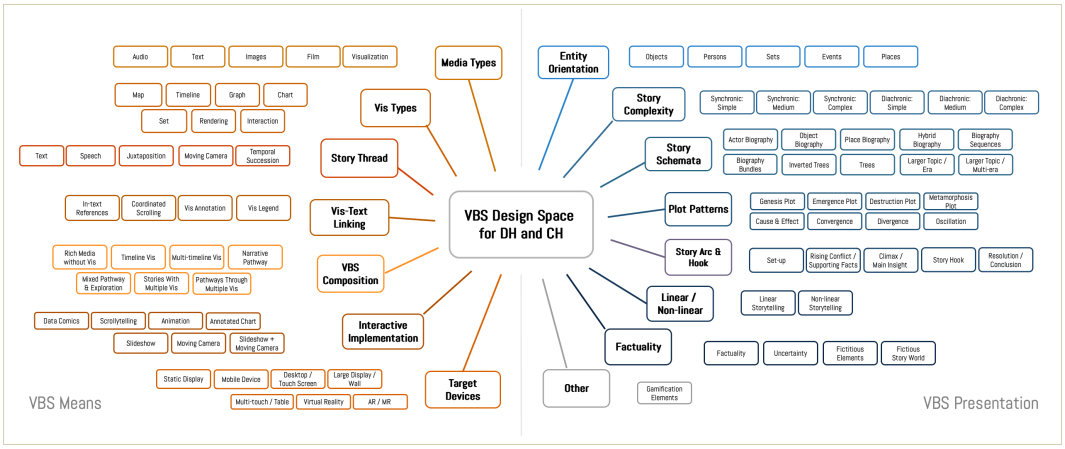

Figure 2.2: Overview of the design space for visualization-based storytelling (VBS) in digital humanities (DH) and cultural heritage (CH) fields for the analysis of VBS state-of-the-art examples and authoring tools. Analytical categories on the left side focus on technological means and design dimensions available for VBS authors—and is used for the analysis of VBS authoring tools (see Subsection 2.2.6) and state of the art VBS examples. Additionally, the right side categorizes implementation-specific characteristics for VBS examples (see Subsection 2.2.5).

ing newer, web-based, and data-driven stories also, Stolper, Lee, Henry Riche, and Stasko [405], and Gershon and Page [141] extended Segel and Heer's schema by adding other genres (e.g., timelines), narrative structure tactics (e.g., interactive brushing and linking), messaging (e.g., audio), and visual narrative tactics (e.g., linking separated story elements).

Yang, Xu, Lan, Liu, Guo, Shi, Qu, and Cao [469] analyzed the narrative structure of data videos based on Freytag's pyramid [134], which is a prominent model of the classic narrative arc starting from an introduction of a setting (exposition), with a progressive increase of the tension (rising action) towards the climax, and falling tension (falling action) until the end (resolution). They identified narrative patterns, data flows, and visual communication design strategies to support the story's flow through the pyramid. Even though Yang, Xu, Lan, Liu, Guo, Shi, Qu, and Cao [469] analyzed only linear, author-driven forms of storytelling, they argue that their analysis could be extended to other forms of VBS. Similar approaches were taken by Amini, Henry Riche, Lee, Hurter, and Irani [6] to describe the narrative structure of data videos (establisher, initial, peak, release) and Kosara [242] to analyze argument structure for data stories (claim/question, facts/evidence, explanation, conclusion)—which are both based on Cohn's [72] theory of visual narrative structure categories of sequential images.

Latif, Chen, and Beck [259] studied the spatial arrangement and interactive linking of visualization and text as an essential driver of reception, engagement, comprehension, and recall. They identified different options to explicitly or implicitly link text and visualization and embed the visualization in the narration. Introducing the visualization technique of story curves, Kim, Bach, Im, Schriber, Gross, and Pfister [226] analyze the (non-)linearity of narrated fiction (i.e., movies) based on Genette [137] nonlinear narrative patterns. By investigating how the historical sequences of events are ordered in the narration, they extend the classical patterns (chronicle, retrograde, zigzag, analepsis, prolepsis, syllepsis, and achrony) with the patterns beginning/ ending in medias res, continued flashbacks/ flashforwards, staged flashback/ flashforward, bidirectional flashes, and merging/ diverging zigzags.

In another survey of 80 visualization-based stories, McKenna, Henry Riche, Lee, Boy, and Meyer [296] identified seven factors that contribute to the visual narrative flow: (1) how recipients navigate through the story, (2) to what level of detail they can control the text, visualizations, and transitions between, (3) visual information on the story progress, (4) the story layout used, (5) the balance between visualization and text, (6) the linearity of the story, and (7) the kind of feedback users receive when interacting with the story.

In the context of cartographic design, Roth [370] provides three perspectives on visual storytelling: foundational plot patterns (three-act structure of stories containing basic plot patterns, see Subsection 2.2.5), visual storytelling genres (static visual stories, long-form info-graphics, dynamic slideshows, narrated animations, multimedia visual experiences, personalized story maps, and compilations) which are *"defined only by the visual or interactive technique used to enforcing linearity in the narrative sequence"*, and visual storytelling tropes (continuity, mood, dosing, attention, redundancy, metaphor, voice) *"used to advance narratives across text, maps, images, and other multimedia"*.

2.2.3 Survey Scope

The discussed surveys have already explored and classified various general aspects and application fields of VBS. We build on these reflections with the aim to unify, connect, and apply related concepts from these and other works to our focus field for a *topic-centered* survey [297]: We aim to develop a coherent VBS design space for the sprawling fields of DH and CH, which has not seen a systematic discussion and conceptual consolidation until now. As such, we do not aim for an exhaustive, "paper-centered" approach, giving a statistical account on all available contributions in the field [297], but to establish a novel conceptual and analytical framework (i.e. an expressive design space) helping to get a grip on a remarkably complex topic, eluding existing visualization categories, but also DH and CH work until now. For the related development of hybrid analytical categories, we build on a prototypical design space that has been derived in the context of a transnational DH project focusing on CH data [251] which has been further consolidated for this survey (see Figure 2.2). Thanks to the analysis of found existing works and literature review, this design space synthesizes established and novel, rather theoretical, categories to analyze unique VBS examples in DH and CH (left and right hand side in Figure 2.2) and to better understand the essential characteristics of VBS authoring tools (left hand side only), but also to reveal gaps and future potential.

With regard to our survey methodology, we collected VBS approaches to DH and CH data by a predefined selection process (see Subsection 2.2.4). For that matter we assembled examples of VBS authoring tools and existing examples and instances of visualization-based stories in DH and CH fields, either documented by scholarly reflections or published on the web. Thus our guiding criteria for the inclusion of VBS works were:

A. Existing relations to DH or CH domains and projects (e.g., by a chosen topic or by the authors' corresponding affiliations)

B. The utilization of visualization(s)

C. Existing narrative design aspects

Similarly to prior research on VBS in online journalism [427] or scientific papers on VBS [391], we are not aiming for completeness with this investigation but to collect and document VBS instances centered on a specific topic—i.e., on DH and CH phenomena—and for illustrating this "topic-centered" design space categories with a sample maximized for showcasing the diversity of design solutions. Within this sample we highlight representative solutions and best practices to provide guidance for future visualization and DH scholars and analyze each narrative example to gain insights into commonalities, differences, and open challenges. The sample thus illustrates a wide variety of data, topics and narrative technologies throughout the dimensions of our design space, which we consider to reflect at least some aspects of the unique diversity that is inherent to CH and DH.

As an interdisciplinary nexus of fields, the digital humanities combine traditional approaches to the study of arts and humanities topics with computational methods [102, 329, 330, 346]. This involves the use of digital tools, methods, and resources to enhance research, teaching, and learning in the humanities [387]. The goal of many related projects is to create new forms of knowledge and understanding by examining humanities data and cultural archives with computational methods, including visualizations and simulations [47, 66]. The bi-directional interaction between the two fields interconnects traditional humanities methods and practices with computational approaches to enhance workflows and methods instead of replacing them.

Cultural heritage, on the other hand, refers to the inherited traditions, beliefs, customs, knowledge, and artifacts passed down from one generation to another within a particular cultural group, due to their "aesthetic, historic, scientific, or social value" [189]. It encompasses tangible elements, such as monuments, buildings, works of art, manuscripts, and archaeological sites, and intangible elements, such as oral traditions, rituals, music, and dance [435]. With regard to CH, the digital transformation has been understood as a large scale effort to document and duplicate CH collections globally, and thus to create a "4D mirror world" with digital twins of global CH—and modelling its evolution historically via structured and linked data over time [215].

In common practice, DH and CH fields and methods are closely intertwined: While DH develops and adapts computational methods for the study of humanities topic in general—often with a focus on textual sources—CH more narrowly focuses on digital methods for the study of tangible and intangible cultural objects [312]. According to common parlance, DH is understood as the bigger and more inclusive tent [412], which also incorporates CH fields of study. However, the closer inspection of related scholarly communities with their working programs, organizations, and traditions also makes the separated but interrelated reflection on both fields plausible [312], which we chose for our current approach. In this survey, we thus assemble VBS examples from both fields, including stories more narrowly tailored to CH actors, objects or collections, but also story approaches with a high relevance for larger-scale DH reflections in disciplines such as history, politics, literature, archaeology, musicology, media studies, or art history. Certain DH fields are not expressively addressed in this survey, such as philosophy, linguistics, religious studies, or work in the adjacent fields of the social sciences. Nonetheless, we believe that story data arising from these fields can be modeled in similar manners using DH-centric entity classes or combinations of them, as we describe in Subsection 2.2.5.

2.2.4 Methodology

The seminal collection of VBS examples, publications and tools of this survey has been informed and facilitated by the team of authors' existing expertise in the field and by previous surveys (see e.g., [201, 224, 251, 458], as well as works summarized in Subsubsection 2.2.2). In addition, we searched for related work on VBS within the scope of the survey. Since our survey is situated at the intersection of VBS, DH and CH studies, the main resources for this work originate from the according realms. Hence, publications were retrieved from visualization conferences (e.g., the annual EuroVis conference) and journals (e.g., IEEE TVCG), digital humanities (e.g., ADHO Digital Humanities), cultural heritage (e.g., Journal on Computing and Cultural Heritage) and from their intersection (e.g., DARIAH Annual Event 2022: Storytelling, International Conference on Interactive Digital Storytelling (ICIDS)). Furthermore, we utilized Google Scholar to browse visualization and theory related to storytelling using keywords such as "visual storytelling", "data-driven stories", "narratives", "scrollytelling", "geospatial storytelling", and the combination of them to gather academic references. Then, reviewing each paper's related works and sections individually, we traced every cited reference and checked if it fitted our survey scope.

In addition, we used Google Search with similar keywords to find relevant VBS tools, along with examples implemented using these tools. For instance, we encountered DataToon [228] as a relevant VBS editor and took CH and DH showcases into closer consideration (see Figure 2.14). In addition, we did not just look into works or tools arising and described in academia but also into relevant contributions from professionals working in journalism or the arts to include, for example, seminal scrollytelling features published by news providers or cultural heritage institutions. However, we excluded works that do not include *visualizations*.

For a demarcation of this central concept and related examples we built on an inclusive definition of visualizations as "visual representations of datasets designed to help people carry out tasks more effectively" [314], which bridges the common distinction of information and scientific visualization [361]. As a result, our collected VBS examples strongly emphasize instances built around techniques of data or information visualizations (i.e. visual representations of "abstract" data to amplify cognition [62]), but they also include three-dimensional renderings of cultural artifacts, which are of particular importance for (storytelling in) CH fields, often in addition with virtual or augmented reality techniques. This can be illustrated with a "visual" scrollytelling article about the outbreak of and fight against the fire in the cathedral of Notre Dame [322], which is driven by multimedia and annotated three-dimensional renderings and schematics, and thus got excluded (it is also not freely accessible). Whereas the "visualization-based" "Wer heilt hat recht" [170] focus on an interactive timeline and uses three-dimensional renderings only in addition to that to make the matter more tangible.

VBS Sample Description: While the collective search procedure quickly assembled a large number of 123 *VBS examples*, the following selection and winnowing process led to a significant reduction of works selected for the topic-centered analysis based on the defined inclusion criteria. As a guiding selection criterion, we aimed for the maximization of diversity, to illustrate the utilization of as many design space features and cells as possible. Works are included if they primarily revolve around the domains of DH and CH, anchoring our analysis in contexts that resonate with the essence of historical significance and cultural resonance. However, we deliberately steer clear of work on overly contemporary topics and modern data journalism in order to maintain a his-

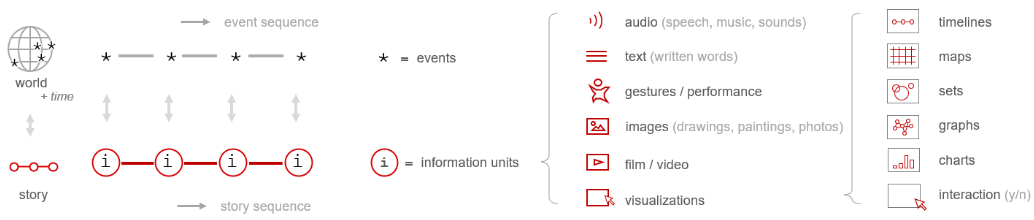

Figure 2.3: Stories narratively encode sequences of events in real, historical, or fictitious worlds (top left) into story sequences, consisting of distinct information units (bottom left), which can be encoded by different types of media (center right, see 2.2.5), including different types of visualizations (right, see Subsubsection 2.2.5).

torical perspective than the immediacy of current events. A key determinant for inclusion is the presence of a recognizable narrative structure, characterized by elements such as a well-defined setting, engaging characters, and a coherent chain of narrative events. This serves as a counterpoint to the exclusion of work that relies solely on exploratory visualization without a narrative thread, a departure intended to underscore the importance of VBS in Digital Humanities. Furthermore, we exclude works that have become inaccessible over the course of the analysis period, ensuring that the material included remains not only relevant but is also readily available for reference and study. In addition, we do not include works that are behind paywalls, as this impedes the open and equitable dissemination of knowledge. Ultimately, the inclusion of multiple examples from identical VBS tools was possible but limited to four instances to avoid redundancy if they were too similar. The final number after curation and filtering according to our criteria amount to 34 VBS examples.

In our selection of *VBS tools* for analysis, we did not strictly focus on tools that, as a core feature, allow the creation of visualizations. We also incorporated tools that, in other ways, offer features that facilitate the integration of visualizations with narratives. Some of these tools excel in annotating, combining, or coordinating images of data visualizations, still making them valuable for composing VBS. For instance, certain tools that emphasize rich media content creation, without the direct ability to process data and generate visualizations, found their way into our study. This inclusion was driven by their evident design or usage focus on annotating visualization images. An example of this category is VizFlow [408], which—while not primarily a data visualization tool—offers capabilities catering to VBS authors' needs.

Coding Procedure: Regarding the analysis of collected VBS examples and tools across our design space categories, we followed a double coding process: Two authors from different groups independently assessed each VBS example. Coding discrepancies were resolved after a collective discussion on a case-by-case basis.

2.2.5 A VBS Design Space for DH and CH

In the following, we assemble a design space for VBS in the fields of DH and CH. For this purpose, we bring together design dimensions from the literature, referenced in Subsubsection 2.2.2, enrich them with additional DH and CH perspectives, and interweave them with specific design considerations emerging from an extended understanding of story protagonists (which we refer to as entities of interest in Subsubsection 2.2.5). Along the way, we illustrate essential design space characteristics by linking them to representative VBS examples while we analyse them. The coded VBS examples and tools are available in an interactive survey browser under `https://intavia.github.io/`.

Media Types

Techniques of storytelling are guiding and organizing communication efforts across different media types—especially in multimodal "new media" environments. As such, readers and designer benefit from looking at the elementary media units of a story: Which media elements does a story—or does a VBS tool allow to—interweave? With regard to the basic story structure laid out in Figure 2.1 (right-hand side), we distinguish different media types available in digital design settings to encode and represent the elementary 'information units' of stories (see Figure 2.3). These different media types include *sound or audio information* (speech, music, noises), *text* (written information), *gestures or performative elements* (for direct narrative presentations), *images* (drawings, paintings, photographs), *film or video elements*, and *visualizations*. From this general point of view, visualizations are just one content or media type that commonly is carefully interwoven with other media types to multimodally represent complex DH and CH information. In this regard, audiences of digital environments are used to encounter all kinds of narrative "multimedia" designs—for instance, historical documentaries, which combine the speech of a narrator with (historical) images, music, and diagrams [160]. In this context, the utilization of media types can happen in parallel (e.g., a video stream with a synchronous track of spoken commentary) or as a temporal sequence of the different media components (similar to the analysis by Latif, Chen, and Beck [259]).

In most of our analyzed examples, the main narrative is conveyed by textual information accompanied by images to illustrate the story. Only in the case of video or filmmaking approaches, narrators are used to develop the story thread via voice-over in a documentary style (e.g., Halloran [160], see Subsubsection 2.2.5). In general, audio is mostly used as part of film sequences or as sound effects to contextualize and increase the receptive immersion with a denser atmosphere via related audio or additional video sequences [112, 186, 210]. The use of sounds or music becomes more substantial if the actual story revolves around music, such as the story of new beat inspiration [304], the development of men's pitches throughout history [286], or musical instruments and their sustainability [253]. We encountered the use of speech to directly present perspectives in VBS examples only in the rarest of cases such as in case of the first-person insights on cultural objects in case of the various Austrian historical collections [170].

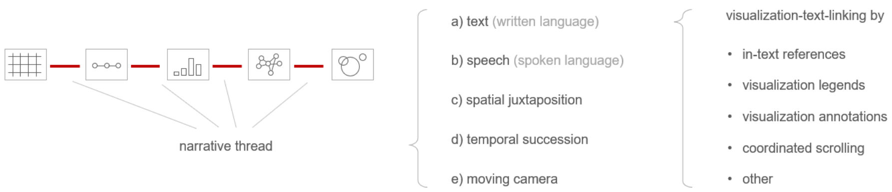

Figure 2.4: Different possibilities for creating a narrative thread between visualizations or other media types (center). In the case of text used to convey the narrative, the linkage between it and the visual element gains in importance (right, see Subsubsection 2.2.5).

Visualization Types

VBS designs essentially depend on the choice of visualization techniques which are utilized by a story or offered to the users of a VBS tool. To simplify the corresponding categories, we distinguish timeline visualizations from map-based visualizations, set-based visualizations, network graphs (including trees), different types of statistical charts (such as bar, pie, line, or area charts), and three-dimensional renderings. For these different types of encoding DH and CH data, we also analyze whether they are implemented as interactive or static visualizations (see Figure 2.3, right hand side).

With their focus on chronological sequences of events, *timeline visualizations* are a near universal visualization option for data stories. In DH and CH practice, timelines often focus on representing a selected actor's trajectory, such as stations of an individual's biography in case of artists Mary Kearn [285] or Whitney Houston [237]. But also analyses of large aggregates of individuals are feasible use cases, such as the fallen of World War II [160], whereby timeline representations are often accompanied by other visualization techniques (such as line or bar charts), contextualizing the chronological sequence of events. Related examples reflect on the different painting styles of Vincent van Gogh [403] throughout his career with a synchronous look at his working locations on a *geographic map*. Similarly, the changing manufacturing conditions for musical instruments have been visualized with regard to the plant and animal species used as resources against the threats of biodiversity loss [253]. In a complementary fashion, geospatial information on maps is oftentimes contextualized with trajectory visualizations to represent spatiotemporal movements and journeys throughout a character's lifetime [124, 325]. *Statistical charts* are frequently used to add further context and to enrich stories with quantitative information or with *set-typed visualizations* of groups and clusters of multiple entities and their development throughout the story. Examples include the depiction of army strengths during Napoleon's war campaign against Russia [415] or the orchestration of musical instruments throughout the career of Miles Davis [228]. However, the visualization of set-typed data and even more so the representation of relational data in form of *network graphs* remains a rarity within the analyzed VBS examples, which makes the use of these visualization types interesting for future storytelling projects. Most of the visualizations analyzed by this survey have been implemented in an interactive fashion to allow recipients to explore selected data and to drill down on further details on demand. Through those characteristics the visualizations are able to tell stories by themselves, but most often they act more as depiction of the narration delivered through further elements.

Story Thread & Visualization-Text Linking

There are multiple options to interweave multiple media or visualization elements to carry the *story thread* of a VBS instance. The dominant threading technique is the use of (the referentiality of) language, either as written text or as spoken narrative voice. As such, the guiding question is: How are language-based story threads and visualization elements interlinked (cp. [259, 296])? Regarding visualization-text linking, we distinguish *in-text references to visualizations* from *legends of visualizations*, *narrative annotations of visualizations*, or *coordinated scrolling techniques* (see Figure 2.4, right). However, story threads can also be generated by non-linguistic techniques (see Figure 2.4, center), such as the *spatial juxtaposition* of visualization and media elements, or their *sequential chaining* utilizing temporalization and chronological transitions (e.g., with a slideshow), or by a *moving camera*, which pans and zooms into various selected elements of a larger visual constellation, including various subtypes of established part-to-part or part-to-whole transitions (cp. [293, pp. 60–93]).

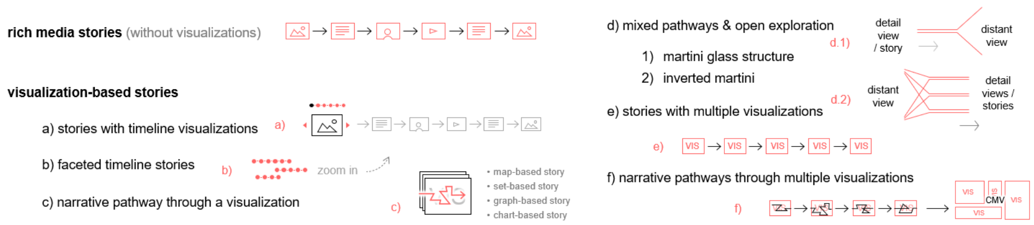

Figure 2.5: Basic composition options for visualization-based stories, ranging from linear, timeline-based media sequences (top) to complex narrative pathway designs (bottom), see Section 2.2.5

In most of our analyzed VBS examples, a 'moving camera' is used in combination with maps to follow a character's spatiotemporal pathway, like the progression of the revolt on Jamaica in 1760 [53] or by panning along a timeline with eras for Austrian cultural heritage collections [170]. In contrast, juxtaposition designs line up different story states side by side for sequential inspection, such as with data comics [228] or the card-styled story of Spades in African-American communities [135]. A similar design—but with a sequential revelation of states—has been chosen for the depiction of temporal pattern succession in paintings by Vincent van Gogh [403], or after each click for the differences in men's pitch throughout the years [286]. For the widely used technique of scrollytelling, coordinated scrolling moves readers along the story thread to trigger further actions, reveal additional multimedia context, and to introduce or update visualizations (e.g. [253, 402]).

Visualization-Based Story Composition

There are different options how visualization-based stories can be composed; how visualizations are built into stories, or how "author-driven" design elements enrich and structure largely "reader-driven" visualization components [391]. For the analysis of composition options for VBS approaches (see Figure 2.5), we start from the baseline case of *rich-media stories*, which connect multiple media elements (including all media types from images to texts, video, audio) without visualizations through a narrative thread. They provide a multi-sensory experience that can en-

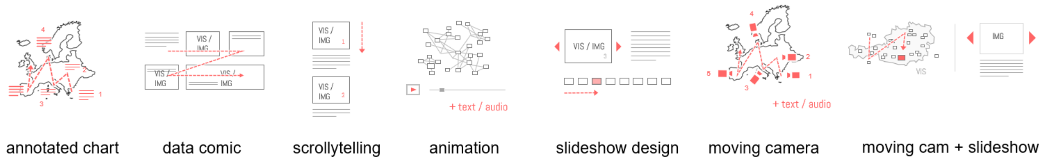

Figure 2.6: Prototypical interactive implementation options for VBS. Considered aspects here are the transitions between visualizations and information throughout the thread of "story states".

gage audiences more deeply than single-medium narratives. This approach is particularly useful in CH settings where the goal is to recreate or simulate historical environments, traditions, or experiences. It allows for a rich, immersive experience that can convey the ambiance of a historical period or cultural setting [25, 337, 365]. While these stories are a borderline example—technically external to our survey scope, even though they represent the majority in digital storytelling—we consider rich media sequences to often provide the building blocks or source material for more complex VBS designs. For instance, rich media stories often are accompanied by a) a *timeline* which shows all plot points as chronological markers on a time axis. Alternatively, b) *multiple timelines* can visualize (parallel or interconnected) story threads, which again are depicted in more detail by rich media elements. Another central composition principle is given by c) *narrative pathway designs*, which can lead through any visualization, such as map, set, graph, or chart-based arrangements. This method helps in maintaining narrative coherence and ensuring that the audience grasps the intended message or storyline and are useful in e.g. museum exhibits or digital archives, where guiding the audience through a specific narrative (like the life of an artist or the development of a cultural movement) is desired. In the following, d) "mixed" (author-and-reader-driven) pathway designs either instantiate the d.1) *Martini glass structure* (where an author-driven story sequence introduces the reader-driven visualization, according to [391]), or d.2) *"inverted Martini" pathways*, which users can activate and follow in an author-driven manner according to details-on-demand (also "drill-down structure", cp. [391]). These structures are valuable in educational settings or interactive exhibits where the goal is to initially provide a guided understanding before allowing exploration, or vice versa. For example, initially guiding a user through the critical stages of a historical event, then allowing them to explore related artifacts or documents in-depth. In addition, we consider e) *sequences of multiple visualizations* to be a relevant design strategy, which can translate the design principle of multiple or faceted views into a narrative perspective. Those are useful in comparative studies or when showcasing diverse aspects of a cultural heritage topic, like comparing architectural styles across different civilizations or presenting various facets of a complex historical event. If such a narrative visualization sequence is combined with further narrative pathways through the individual visualizations, the nested design of f) *narrative pathways through multiple visualizations* are the result (see Figure 2.5).

At a first glance, the correlation between VBS examples and timeline visualizations, and the use of narrative pathways through geospatial map visualizations becomes apparent. The use of this technique throughout further visualization types such as graphs and sets are missing—most likely due to the general lack of these visualization types. Multiple timelines occur only in very few cases, and there mostly to compare different categories in lanes, like it is apparent in case of the different regions around Salzburg, Austria [170]. Mixed pathways (through multiple visualizations) and exploration options break up the author-driven path, create pauses, and allow for interaction in-between as well as details-on-demand to create a rather complex and multi-modal VBS experience (e.g. [253, 403, 415]).

Interactive Implementation Options

In a rather complex space of design options, we highlight prototypical designs, where the story thread either unrolls in space (juxtaposed scenes and story elements) or in time (sequential, time-oriented storytelling). Implementation options include a) *annotated visualizations* [357], where numbered text blocks (and arrows) add a story-layer to a static visualization, b) *data comics* [21], as juxtaposed panels of visualization or images, commonly combined with text, c) *scrollytelling designs* [279], which similarly juxtapose visualizations or image-based media chunks with paragraphs of text, often enriched by other interactions (also called "long form info-graphics", "multimedia visual experiences" or "compilations" [370]), d) *narrated animations*, where a changing visualization (or a film-sequence of content chunks) tells a story - e.g., together with an audio or text track, e) *dynamic slideshows*, which allow clicking through a sequence of all possible media types, f) *moving camera*, where a camera pans and zooms into a visualization (usually combined with additional story information), and g) *combined moving camera+slideshow designs* (see Figure 2.6).

The majority of coded storytelling examples are realized by either scrollytelling (e.g. [135, 253, 304]) or slideshow techniques (e.g. [99, 210]), but both often in combination with moving camera approaches to keep the focus within the visualization. In contrast to that we just found single examples using a data comic on "Miles Davis' Famous Albums & Featured Musical Instruments" ([227]; see Figure 2.14), connecting musicians with related instruments throughout the different panels.

Target Devices

While many story implementations (or tools) allow reception on multiple devices or platforms, some VBS examples or tools are tailored to (or aim for) specific devices, including a) *static displays* (e.g., posters, textbooks, museum catalogs, exhibitions walls), b) *touchscreens or desktop* only, c) *mobile devices* (smartphones or tablets), d) *large public displays or wall projections*, e) *multi-user devices* (e.g., multi-touch interfaces or tables), f) *virtual reality devices*, or g) *augmented/mixed reality devices* (see Figure 2.7).

Throughout the analysis we found most of the examples designed for the responsive perception via desktop or mobile devices, whereas only a few examples focus on mobile consumption or explicitly expect a desktop resolution such as the story on the patterns in the life of Vincent van Gogh [403]. We only encountered a few examples specifically designed for augmented/mixed reality where all of them forego information visualization and mainly focus on realistic renderings often in combination with gamification elements such as the watering and growth of a coffee plant [126].

Entity-Orientation

Storytelling in DH and CH can revolve around any kind of narrative entity as a story protagonist. These can obviously be a) persons, but also b) objects, c) (historical) events, d) places, or e) sets in terms of complex combinations of all of these entities (see Figure 2.8).

Persons include all kinds of (historical) figures and human actors. Many CH and DH stories shed light on histories of individual persons and on their changing characteristics and situations, such as the development of the instrumentation in albums by Miles Davis via juxtaposed graphs as a data comic [227].

Objects refer to all kinds of natural or artificial things, especially CH objects such as paintings, documents, sculptures, movies, buildings, or other artworks. DH and CH scholars are frequently

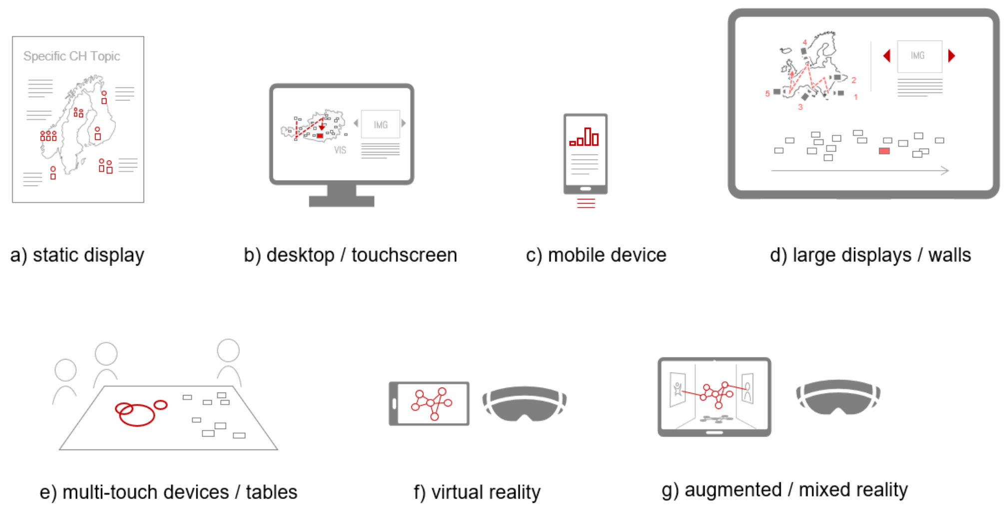

Figure 2.7: Range of target devices which are frequently encountered in DH and CH-centered VBS contexts.

Figure 2.8: Major entities of interest in fields of digital humanities (DH) and cultural heritage (CH), which are narratively interwoven by synchronic and diachronic relations.

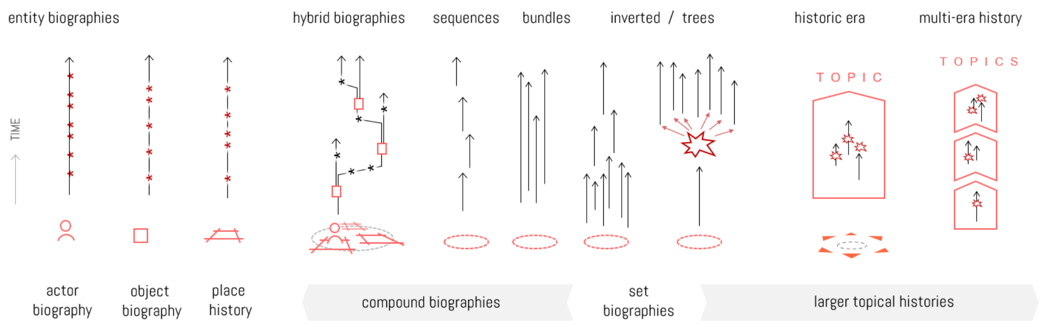

Figure 2.9: Story schemata, from individual entity biographies (left) to increasingly complex set biographies (right).

interested in the provenance and stories of such objects. For instance, users are able to locate the history of Titian's paintings in time and space [75].

Events refer to historical occurrences that trigger more consequential state changes of large sets of entities, such as natural disasters, social unrest, reforms, or wars. Often, VBS stories about events in history refer back to persons and/or objects, but they can be a story focus of its own. Examples are war campaigns like Napoleon's 1812 campaign against Russia [415] or the attack on Pearl Harbor [112].

Places refer to spatial and geographic constellations such as buildings, villages, towns, or whole countries. Related VBS examples illuminate the developments of the Austrian city Tulln, told by an interactive museum app [127] or the life in concentration camps for more than 120000 Japanese Americans in the USA between 1942 and 1946 [114]. Even when they are not a focused entity, places frequently organize geo-spatial storytelling by the utilization of maps (e.g. [315, 423]) due to their links to cultural objects and persons.

Sets are larger aggregations of multiple entities and focus on their relationships using contextual information. As such, this category can refer to sets of persons (groups, families, organizations),

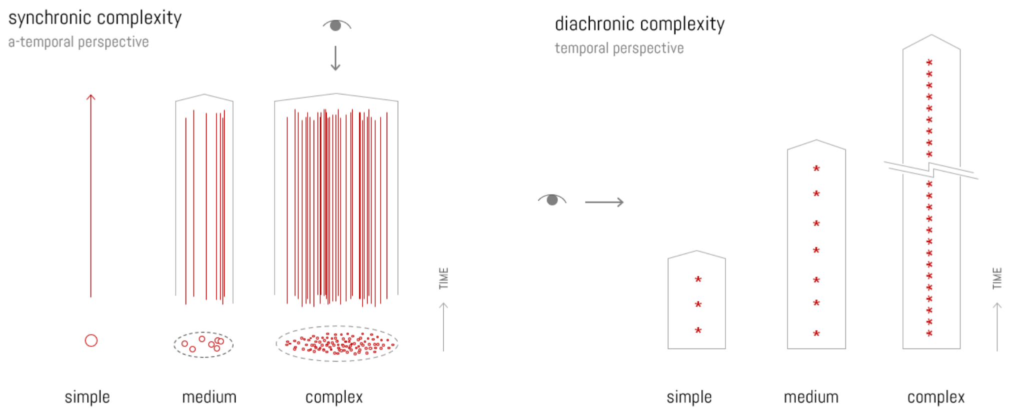

Figure 2.10: Story complexity from a synchronic (left) and a diachronic perspective (right).

sets of objects (e.g., collections, exhibitions), sets of sets (e.g., clusters of art schools), sets of (historical) events (e.g., history of secularization), or sets of places (e.g., all places of a political territory). Exemplarily, "Objects of Wonder" tells the story of 147 million items in the collections of the Smithsonian Museum of Natural History and reflects on challenges of biodiversity with various collection objects [402]. Frequently the different connected compounds of sets or subsets are used to compare similarities and differences such as in the case of the painting throughout various areas and periods revealing the "Patterns in the life of Van Gogh" [403].

Story Complexity

For analytical purposes, we introduce two simple complexity measures for VBS instances using approximate categories for synchronic (non-temporal) diachronic (temporal) story complexity (see Figure 2.10).

Synchronic story complexity is given by the number of focused entities the story revolves around and in this context we distinguish three complexity levels: *Simple* equals an entity focus of one, as is the standard for individual biographies (e.g. [285, 315]) or a or specific, narrow topic (e.g. [126, 304]). *Medium* derives from a focus on multiple entities and countable composites (e.g. of objects [253, 402] or of places [128, 138]). *Complex* corresponds to a focus on a large number of composite entities beyond immediate countability. Examples include stories on war campaigns (e.g. [112, 160, 415]) and utilize distant reading approaches rather than detailed analyses of single entities.

Diachronic Story Complexity is given by the number of narrative events and roughly corresponds to the length of a story and its narrative granularity. Again we distinguish three levels: *Simple* describes short stories with relatively coarse temporal granularity (e.g. [186, 210]). *Medium* describes medium story length and medium temporal granularity (e.g. [135, 233]). While *complex* is ascribed to VBS examples with an extended length and high temporal granularity, spanning whole lives or even multiple eras (e.g. [285, 349]).

Story Schemata

Story schemata describe the organization and internal narrative architecture of stories, which are characterized by the synchronic and diachronic combination of entities. We identify a range of prototypical DH-centric story schemata, as illustrated in Figure 2.9, from actor, object, and location-based biographies to a whole spectrum of set biographies. This synopsis also clarifies that most individual and collective stories practically count among the large class of set biographies, bundling the stories of various other entities and actors into a larger narrative. To the right-hand side of the spectrum of story schemata, we find the category of larger historical topics, which are large-scale constellations (i.e., the subject of numerous historiographic endeavors), beyond entity-based modeling and visualization.

Plot Patterns and Structures

Plot patterns or plot structure refer to the internal structure of a story characterized by the types of events that are connected sequentially to the overarching story plot. A lot of structural knowledge already exists about recurring plot patterns in stories, which we consider to be of poten-

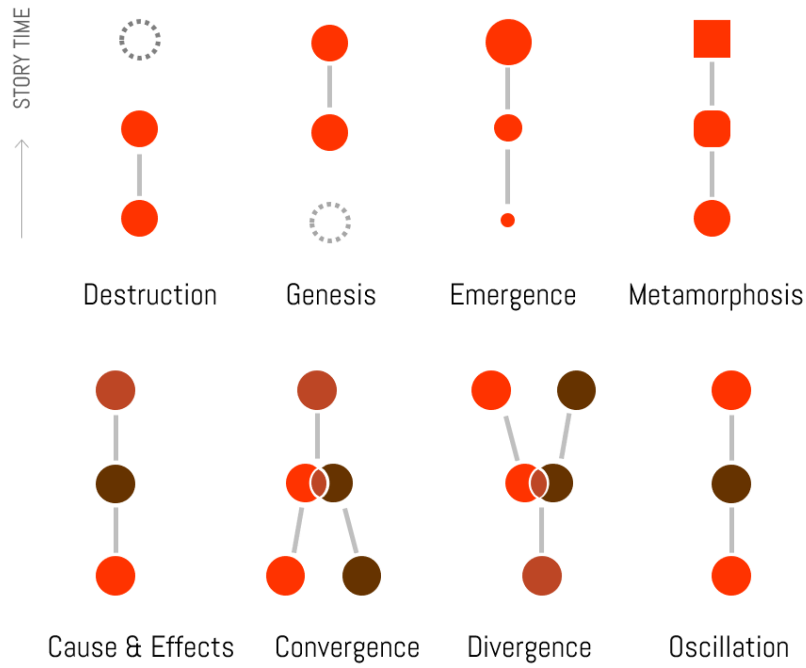

Figure 2.11: Plot patterns for story protagonists (top) and for protagonist and antagonist combinations (bottom). Adapted from Roth [370].

tial interest for VBS. Exemplarily, Roth summarizes how a foundational three-act structure of stories—known since antiquity—frequently organize narrations about a story protagonist's fate [370]. These include *genesis plots*, *emergence plots*, *destruction plots*, and *metamorphosis plots* (see Figure 2.11, top). Given a story antagonist, frequently reoccurring plot patterns include *cause and effect*, *convergence*, *divergence*, and *oscillation plots* (see Figure 2.11, bottom). We analyze if visualization-based stories in the DH realm build on similar plot patterns—or if such patterns could be strengthened in the long run to add narrative engagement to the rather sober, academia-adjacent genre of VBS designs (see the discussion of future challenges in Subsection 2.2.8).

Story Arcs & Hooks

Stories are known to be engaging design strategies because they draw their audiences into a reception process that unfolds a continuous pull on the reader's attention. In line with the classical three-act model, a prominent conception of "*story arcs*" supposes them to show a pyramid-like shape [370]. Figure 2.12 shows how such a prototypical arc develops from the story set-up over rising conflict to reach a resolution after a climatic transition. Yang, Xu, Lan, Liu, Guo, Shi, Qu, and Cao [469] revised this plot structure to analyze data stories, including the set-up of a background, and a central rising-climax phase, which builds to a main insight based on supporting facts and reaches a resolution or conclusion thereafter. "*Story hooks*" are essential engagement elements in the set-up scene of a story, which grabs and captures the readers' attention or imagination and pulls them into the story [370]. According to Dykes [105] the VBS context this is often a notable

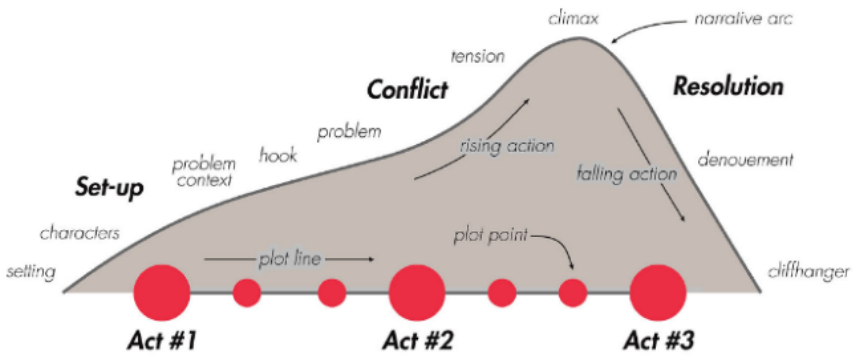

Figure 2.12: Story arc with a three-act structure (from [370]).

observation in the data which introduces the problem. In our examples it seems that this "engaging pull" relies on the scripted story arc, typical for a more author-driven design in opposite to the more explorative stories with more freedom for the user.

Story Linearity or Non-linearity

While story sequences often linearly mirror the sequence of historical events (see Figure 2.3), advanced storytelling employs a wide variety of non-linear storytelling techniques. Kim, Bach, Im, Schriber, Gross, and Pfister [226] made such "story curves" visible by combining the historical sequence and the narrative sequence in an orthogonal fashion. As such, we analyze VBS designs with regard to VBS non/linearity.

Factual, Uncertain & Fictional Stories

Stories are free to combine factual and fictional elements or to invent new story worlds completely. Factual stories are used to narrate historical knowledge, even though the explication of (data) uncertainty is a major topic in DH and CH fields (see, e.g., [458, 464]). However, VBS can also guide through the fictional worlds of historical artworks, can be inspired by existing places in Dante's Inferno [210], or show a character's path through the fictional world of Game of Thrones [233].

Gamification Elements

An additional layer of recipients' engagement can be achieved by utilizing gamification strategies in VBS. As such, we analyzed whether visualization-based stories also include game-based affordances and interactions. In more detail, we also discuss this design strategy to raise the attention as a future challenge due to the given implementation gap in Subsection 2.2.8.

			Media Types					Vis Types						Story Thread					Vis-text Linking					VBS Composition							Int. Implementation							Target Devices						
Category & Name	Availability	GUI	Audio	Text	Images	Film	Visualization	Timeline	Map	Set	Graph	Chart	Interaction	Text	Speech	Juxtaposition	Temporal Succession	Moving Camera	In-text References	Vis Legend	Vis Annotations	Coordinated Scrolling	Other	Rich Media Without Vis	Timeline Vis	Multi-timeline Vis	Narrative Pathway	Mixed Pathway & Exploration	Stories With Multiple Vis	Pathways Through Multiple Vis	Annotated Chart	Data Comics	Scrollytelling	Animation	Slideshow	Moving Camera	Slideshow + Moving Camera	Static Display	Desktop / Touch Screen	Mobile Device	Large Display / Wall	Multi-touch / Table	Virtual Reality	Augmented / Mixed Reality
General Vis:																																												
Flourish [122]	C	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓	✓			✓			✓	✓		✓		✓	✓	✓		✓		✓	✓	✓			
Microsoft Power BI [305]	C	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓			✓	✓	✓			✓			✓	✓		✓			✓	✓		✓	✓	✓	✓	✓			
Looker Studio [150]	C	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓			✓	✓				✓	✓	✓	✓	✓	✓	✓				✓			✓	✓	✓	✓			
StoryFacets [338]	R	✓		✓	✓	✓	✓		✓			✓	✓	✓		✓	✓			✓	✓						✓	✓	✓		✓				✓				✓					
Tableau [413]	C	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓	✓			✓			✓	✓				✓	✓	✓	✓	✓	✓	✓			✓	✓			✓	✓	✓	✓			
Qlik Sense [348]	C	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓			✓	✓				✓	✓	✓	✓	✓	✓	✓				✓			✓	✓	✓	✓			
InTaVia Story Creator [271]	R	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓			✓	✓	✓	✓	✓	✓							✓	✓							✓		✓	✓				✓
Map-based:																																												
ArcGIS StoryMaps [113]	C	✓	✓	✓	✓	✓	✓		✓			✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓			✓	✓	✓	✓	✓		✓	✓	✓	✓			✓	✓				
Historypin [397]	C	✓		✓	✓	✓	✓		✓				✓	✓		✓	✓	✓			✓			✓			✓	✓									✓		✓	✓				
Humap [182]	C	✓		✓	✓		✓		✓				✓	✓		✓	✓	✓			✓						✓	✓									✓		✓	✓				
Neatline [384]	O	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓		✓		✓	✓		✓			✓	✓		✓	✓	✓							✓			✓					
StoryMapJS [235]	O	✓	✓	✓	✓	✓	✓		✓				✓	✓		✓		✓		✓	✓			✓			✓	✓									✓		✓	✓				
SMBVT [187]	R	✓	✓	✓	✓	✓	✓	✓	✓				✓	✓		✓	✓	✓		✓	✓				✓		✓	✓							✓		✓		✓					
Visualeyes [395]	R	✓		✓	✓	✓	✓		✓	✓			✓	✓		✓		✓			✓				✓			✓								✓			✓					
Timeline-based:																																												
Tiki-Toki [448]	C	✓		✓	✓		✓	✓					✓	✓			✓				✓				✓			✓								✓			✓					
TimelineJS [236]	O	✓	✓	✓	✓	✓	✓	✓	✓				✓	✓		✓	✓			✓	✓				✓		✓								✓				✓	✓				
Timeline Storyteller [49]	R	✓		✓	✓		✓	✓		✓			✓				✓			✓	✓				✓	✓	✓			✓				✓	✓				✓					
TimeMapper [426]	O	✓		✓	✓		✓	✓	✓				✓	✓		✓	✓	✓	✓		✓				✓		✓	✓							✓		✓		✓	✓				
Chart Annotation:																																												
ChartAccent [357]	R	✓		✓	✓		✓					✓		✓			✓			✓	✓						✓							✓				✓	✓					
Ellipsis [375]	R	✓		✓			✓	✓	✓			✓	✓	✓		✓	✓			✓	✓				✓		✓	✓			✓			✓	✓				✓					
StorylineJS [234]	O	✓		✓			✓					✓	✓	✓		✓	✓				✓						✓				✓								✓					
Data Comic:																																												
DataToon [228]	R	✓		✓	✓	✓	✓			✓	✓			✓		✓				✓	✓						✓			✓		✓						✓	✓	✓	✓			
ToonNote [214]	O		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓						✓	✓			✓			✓		✓			✓		✓					✓					
AR/VR & 3D Vis:																																												
Flow Immersive [123]	C	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓		✓	✓		✓	✓				✓		✓	✓			✓			✓		✓			✓				✓	✓
ThingLink [424]	C	✓	✓	✓	✓	✓									✓		✓							✓				✓								✓			✓				✓	
Vizrt [439]	C	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓		✓	✓						✓			✓		✓					✓		✓			✓	✓	✓			✓
Document Creation:																																												
Idyll Studio [73]	O			✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓		✓			✓		✓				✓	✓	✓				✓	✓				
Jupyter Notebooks [232]	O		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓			✓	✓			✓			✓		✓		✓			✓	✓				✓	✓				
Multi-media Content:																																												
Narralive Story Maker [319]	C	✓	✓	✓	✓	✓								✓			✓							✓			✓								✓				✓	✓				
Shorthand [399]	C	✓	✓	✓	✓	✓								✓		✓		✓			✓	✓		✓			✓		✓				✓						✓	✓				
VizFlow [408]	R	✓		✓	✓	✓								✓							✓	✓		✓			✓		✓				✓						✓	✓				

Table 2.1: The collection of selected VBS authoring tools. The checkmark icon (✓) indicates that a tool in question implements the functionality allowing the creation of VBS with a specific characteristic or feature. The letters in the "Availability" column indicate the following: O indicates that a tool in question is open-source and publically available, and C indicates the tool is a commercial product. In contrast, R means the tool is a research prototype or product with possibly limited accessibility. The coded VBS authoring tools are available in an interactive survey browser under https://intavia.github.io/.

2.2.6 Storytelling Authoring Tools

A VBS authoring tool is a piece of software designed to help a user to create, edit, and display data in a visual format interwoven with a narrative ranging from simple annotated charts to more complex interactive visualization compositions arranged in multi-scene narratives. Ultimately, VBS tools make it possible to put the various practical and theoretical concepts, discussed in Subsection 2.2.5, into play. In this context, analyzing and assessing existing VBS tools can provide valuable insights that extend beyond the identification of core practical and theoretical concepts, i.e., by studying the strengths, weaknesses, and limitations of current tools, VBS tool developers can gain a contextual understanding of gaps and trends that informs the development of future tools tailored to specific requirements. Furthermore, assessing existing tools facilitates iterative improvement by learning from past successes and failures, allowing for refinement and enhancement. It also promotes innovation and differentiation by exploring new techniques and functionalities that set editors and tools apart. Thus, considering existing editors and tools is crucial for developing impactful VBS tools in the future. Furthermore, providing a current overview of tools available can guide new aspiring VBS authors to the right tool to create their intended visualization-based stories.

The collection of tools we presented in Table 2.1 does not have a corresponding VBS example in the analysis presented in Table 2.2 in every case. The collection in Table 2.1 includes tools that have the features available for authoring VBS (i.e., tools that, as a minimum, include components that allow interweaving data visualizations with a narrative) and which may be of use to aspiring VBS authors. A total of 32 authoring tools were found through the application of our search methodology presented in Subsection 2.2.4. The final selection of tools range from some widely-used, popular and mature tools (such as Microsoft Power BI [305], Tableau [413], etc.) to research prototypes (e.g., DataToon [228] and VizFlow [408]) and more accessible open-source tools (e.g., StoryMapJS [235] and TimelineJS [236]).

Categorization & Analysis

The VBS tools have been analyzed according to the VBS means (the left half of our design space in Figure 2.2), as these pertain to the more technological aspects and features of VBS tools. In contrast, the right side of the design space holds more details related to how a VBS author decides to implement and present a specific story and its elements. Furthermore, we indicate in the analysis of VBS tools their *availability and type*, i.e., whether a specific tool is a commercial product, a research prototype, or an open-source tool. As it may be useful to future VBS authors, we will also indicate whether each tool comes with a *graphical user interface* (GUI) or, on the other hand, requires programming skills.

The VBS tools shown in Table 2.1 have been grouped based on their defining features (strengths and weaknesses) to offer a clearer perspective on the range of VBS authoring tools. This emphasizes their applications and utility. The broad array of tools listed means some naturally fall under several categories, given their breadth of capabilities. For a discussion of overall trends and gaps resulting from the analysis of tools, we refer the reader to the discussion of open challenges in Subsection 2.2.8. In the following, we describe the defining features of each category of tools:

General Vis: General vis tools are comprehensive tools for analyzing, visualizing, and sharing data insights. They typically boast a broad range of data visualization features. They often integrate seamlessly with various business systems, enabling users to extract, transform, share, and present data to drive informed decision-making. These tools offer the ability to create interactive dashboards that provide cohesive views of key insights with a rich palette of visualization options, including a wide variety of media types. The primary storytelling features of these tools typically allow for sequenced, annotated visual narratives in terms of a slideshow with interactive visualizations. Due to their primary focus on the creation of dashboards and interactive ensembles of visualizations—possibly compiled into a slideshow—they provide means of seamlessly adjusting and scaling content on display, making them able to target a large set of devices, compared to other tools.

Map-based: Map-based tools intertwine narrative content with geographical contexts, enabling stories to take shape across space. Central to their storytelling capabilities, these tools offer interactive exploration juxtaposed with multimedia enhancements. Some tools even offer the integration of a timeline visualization, providing not only a spatial lens but also a temporal dimension. This integration captures the progression or narrative evolution over time, offering a dual perspective.

Timeline-based: Timeline-based tools specialize in chronologically presenting narratives, emphasizing events' evolution and progression. These tools accentuate storytelling by integrating multimedia elements, offering diverse temporal scales from historical epochs to specific hours and, in some cases, merging the temporal sequence with spatial mapping. They can capture and convey cause-effect relationships, historical context, and development trends through visually rich timelines, making them indispensable for comprehensive and engaging chronological narratives.

AR/VR & 3D Vis: This category of tools encompasses tools designed to facilitate the creation, management, and display of data and narratives in augmented reality (AR), virtual reality (VR), and 3D environments. AR/VR and 3D visualization tools pioneer immersive storytelling by embedding audiences within dynamic narratives. Leveraging 3D environments and AR/VR technologies, these tools amplify storytelling with orchestrated camera movements, speech narration, and guided journeys through evolving scenes. The synergy of interactivity, multimedia content linkage, and immersive technology not only presents but engrosses users in a multi-sensory engaging narrative experience. Such immersion transcends traditional storytelling, offering narratives that are not just observed but experienced.

Chart Annotation: These tools transform raw visual data into narratives by empowering storytellers to guide audience attention, provide context, and emphasize pivotal data events using intuitive annotations. By integrating descriptive cues and narrative sequences directly into visualizations, they ensure that the data is not just displayed but distinctly and engagingly communicated, making complex data digestible and meaningful for viewers.

Data Comic: Data comic creation tools intertwine data visualization with the engaging narrative style of comics, where data adopts a voice and character, being embedded within storylines enriched by dialogue boxes, annotations, and traditional comic layouts.

Document Creation: Document creation tools for VBS combine narrative text with live code, visualizations, and other multimedia elements. These tools enable storytellers to craft dynamic narratives where readers can interact with the data, adjust parameters, and explore various facets of the story that combine live code with narrative text, equations, interactive visualizations, images, and more. Such interactivity promotes deeper understanding and engagement, making complex data more approachable and comprehensible.

Multimedia Content: Such tools do not offer visualization capabilities, but rather focus on crafting rich and immersive narratives by integrating various forms of media, including text, audio, and video. While they might not specialize in data visualization, these tools excel in producing engaging content that weaves together diverse media elements through annotations and coordinated scrolling to provide richer context for readers.

Trends & Gaps

In the following we highlight the overall trends and gaps resulting from the analysis of storytelling authoring tools:

With respect to *media types*, nearly all tools allow working with and including text, images, video and different types of visualizations. Surprisingly, only half the tools allow incorporating standalone audio (not just embedded as e.g. a YouTube video). This limitation can be significant in DH and CH, where audio (like oral histories or ambient soundscapes) can play a crucial role in storytelling.

The variety of *visualization types* ranges between tools. Most of the tools are concerned with timelines, maps, and charts and allow various types of interaction with these types of visualizations. Only a third of the tools provide the capabilities of working with set and graph visualizations. This lack hinders the ability to represent complex relational data and interconnected stories, which are common in historical and cultural narratives.

The primary way of creating a *story thread* is through plain text, while the least used means is through speech synchronized with the content on display. This trend overlooks the potential of oral storytelling traditions, which are essential in many cultures and could enrich digital narratives in humanities and heritage projects.

Surprisingly, not many tools allow the explicit interactive *link between text and visualization*. Most tools implement a rather simple set of methods for linking visualizations and text such as annotations or legends. A few tools have the functionality of creating stories through coordinated scrolling i.e., scrollytelling. This fact restricts the ability to create dynamic and interactive narratives that could enhance user engagement and understanding in cultural and historical contexts.

With respect to *VBS compositions*, most tools allow creating a single narrative pathway through a visualization or allow mixed pathway and exploration. A few tools allow creating more complex VBS compositions, but since these tools are general business intelligence tools the end-results are somewhat rudimentary, in the sense that the VBS compositions appear in terms of a sequence of interactive slides (sequential multi-scene narratives). Most of the surveyed tools are crated around a specific type of visualization e.g. a single timeline or map. Thus, these are constrained from the start and not suitable for creating multi-timeline visualizations or stories with multiple more intricate visualizations. The focus might limit the ability to create multi-layered stories, crucial in representing the multifaceted nature of cultural heritage.

The *interactive implementation* is mostly simple as annotated visualization typically synchronized with accompanying text, images or video, where users can interactively investigate some details. Data comic and scrollytelling format are the least used forms. Those rarely used formats could offer more engaging and informative ways to present cultural and historical content.

The *target devices* most commonly used by VBS tools are desktop/touchscreen, while some also support the display of VBS on mobile devices. There is a large gap of tools which support large displays, multi-touch tables, or VR/AR. The reason for this gap may be that to support large displays, multi-touch tables, and VR/AR specific considerations will have to be carefully made [8]. But nevertheless this limitation is a missed opportunity in DH and CH, where immersive and interactive experiences on diverse platforms could greatly enhance storytelling and audience engagement.

	Media Types					Vis Types							Story Thread				
Name	Audio	Text	Images	Film	Visualization	Timeline	Map	Set	Graph	Chart	Rendering	Interaction	Text	Speech	Juxtaposition	Temporal Succession	Moving Camera
"Wer heilt hat recht": Ein Aus... [170]	✓	✓	✓		✓	✓					✓	✓	✓	✓		✓	✓
An Infamous Day [112]	✓	✓	✓	✓	✓		✓			✓		✓	✓			✓	✓
Archaeology of Wine [349]		✓	✓		✓	✓	✓					✓	✓		✓	✓	
Are men singing higher in pop ... [286]	✓	✓	✓	✓	✓	✓				✓			✓	✓		✓	
Around the Globe with Reinhold... [124]		✓	✓		✓	✓	✓				✓	✓	✓				✓
Daily Life In The Middle Ages [140]		✓	✓		✓						✓	✓	✓				
Dante's Inferno [210]	✓	✓		✓	✓		✓				✓	✓	✓				✓
Game of Throne Arya's Jouney [233]		✓	✓	✓	✓		✓					✓	✓				✓
History of Whitney Houston [237]	✓	✓	✓	✓	✓	✓						✓	✓			✓	✓
How Wine Colonized The World [437]		✓	✓	✓	✓	✓	✓					✓	✓			✓	
How You Play Spades is How You... [135]		✓			✓		✓	✓		✓			✓		✓		
January 1969: Mapping the Sit-... [35]		✓	✓		✓	✓	✓					✓	✓		✓		
Justice Deferred - Executive ... [114]		✓	✓	✓	✓	✓	✓			✓		✓	✓		✓	✓	
Kosmos Kaffee [126]		✓	✓		✓						✓	✓				✓	
Major Battles in the Napoleoni... [13]		✓	✓		✓	✓	✓					✓					
Map Shows How Humans Migrated ... [186]	✓	✓		✓	✓		✓				✓		✓			✓	
Mapping the “White, Marmorean ... [315]		✓	✓		✓	✓	✓					✓	✓				
Mapping the Catalogue of Ships [385]		✓			✓		✓					✓	✓				
Medieval Philosophers [423]		✓	✓		✓	✓	✓					✓	✓				
Mercator: It's a flat, flat wo... [99]		✓	✓		✓		✓					✓	✓		✓	✓	
Miles Davis' Famous Albums [227]		✓	✓		✓			✓	✓	✓			✓		✓		
Objects of Wonder [402]		✓	✓		✓		✓					✓	✓			✓	✓
Patterns in the life of Vincen... [403]		✓	✓		✓	✓	✓	✓	✓	✓		✓	✓			✓	
Slave Revolt in Jamaica, 1760-... [53]		✓	✓		✓	✓	✓					✓	✓				✓
Southern Literary Trail [138]		✓	✓		✓		✓					✓	✓				✓
The Fallen of World War II [160]	✓			✓	✓	✓		✓		✓		✓		✓			✓
The Giant Squid: When Myth Enc... [143]	✓	✓	✓	✓	✓	✓	✓		✓			✓				✓	✓
The Life of Mary Kearn [285]		✓	✓		✓	✓						✓			✓		
The Travels of Marco Polo | Na... [**MarcoPolo**]		✓	✓		✓	✓	✓						✓				
US Westward Expansion [325]		✓	✓	✓	✓		✓					✓					✓
Virtulleum, Tulln [128]	✓	✓	✓	✓	✓		✓				✓	✓	✓	✓			
Visualization-based Scrollytel... [**MusEcologyScrollytelling**]	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓			✓	✓
When Napoleon Ventured East [321]		✓	✓		✓		✓	✓		✓		✓	✓				✓
Wonky [304]	✓	✓			✓					✓		✓	✓	✓	✓		

	Vis-text Link				VBS Composition							Int. Implementation							Target Devices						
Name	In-text References	Vis Legend	Vis Annotations	Coordinated Scrolling	Rich Media Without Vis	Timeline Vis	Multi-timeline Vis	Narrative Pathway	Mixed Pathway & Exploration	Stories With Multiple Vis	Pathways Through Multiple Vis	Annotated Chart	Data Comics	Scrollytelling	Animation	Slideshow	Moving Camera	Slideshow + Moving Camera	Static Display	Desktop / Touch Screen	Mobile Device	Large Display / Wall	Multi-touch / Table	Virtual Reality	Augmented / Mixed Reality
"Wer heilt hat recht": Ein Aus... [170]	✓		✓	✓		✓	✓							✓						✓	✓				
An Infamous Day [112]	✓		✓	✓							✓			✓			✓			✓	✓				
Archaeology of Wine [349]	✓		✓			✓			✓	✓						✓				✓	✓				
Are men singing higher in pop ... [286]	✓					✓										✓				✓	✓				
Around the Globe with Reinhold... [124]	✓			✓							✓							✓			✓				
Daily Life In The Middle Ages [140]	✓								✓					✓						✓					
Dante's Inferno [210]	✓		✓	✓							✓			✓			✓			✓	✓				
Game of Throne Arya's Jouney [233]	✓		✓					✓										✓		✓	✓				
History of Whitney Houston [237]	✓	✓	✓	✓		✓												✓		✓	✓				
How Wine Colonized The World [437]	✓		✓	✓		✓												✓		✓	✓				
How You Play Spades is How You... [135]	✓		✓							✓				✓						✓	✓				
January 1969: Mapping the Sit-... [35]	✓		✓						✓								✓			✓	✓				
Justice Deferred - Executive ... [114]	✓	✓		✓						✓				✓						✓	✓				
Kosmos Kaffee [126]		✓	✓		✓										✓						✓				✓
Major Battles in the Napoleoni... [13]	✓		✓								✓					✓				✓					
Map Shows How Humans Migrated ... [186]			✓					✓							✓		✓			✓	✓				
Mapping the “White, Marmorean ... [315]	✓		✓			✓		✓									✓			✓					
Mapping the Catalogue of Ships [385]	✓							✓												✓					
Medieval Philosophers [423]				✓		✓		✓										✓		✓	✓				
Mercator: It's a flat, flat wo... [99]	✓		✓	✓							✓			✓			✓			✓	✓				
Miles Davis' Famous Albums [227]		✓	✓					✓		✓			✓						✓						
Objects of Wonder [402]	✓			✓							✓			✓			✓			✓	✓				
Patterns in the life of Vincen... [403]	✓	✓		✓		✓	✓		✓	✓				✓						✓					
Slave Revolt in Jamaica, 1760-... [53]	✓	✓	✓			✓				✓								✓		✓	✓				
Southern Literary Trail [138]	✓			✓				✓										✓		✓	✓				
The Fallen of World War II [160]											✓				✓					✓					
The Giant Squid: When Myth Enc... [143]			✓								✓							✓		✓					
The Life of Mary Kearn [285]	✓	✓				✓											✓			✓	✓				
The Travels of Marco Polo | Na... [**MarcoPolo**]	✓			✓				✓						✓			✓			✓	✓				
US Westward Expansion [325]	✓		✓					✓										✓		✓					
Virtulleum, Tulln [128]	✓							✓													✓				✓
Visualization-based Scrollytel... [**MusEcologyScrollytelling**]	✓	✓		✓							✓			✓						✓	✓				
When Napoleon Ventured East [321]	✓	✓		✓					✓	✓				✓						✓	✓				
Wonky [304]	✓	✓		✓		✓								✓						✓	✓				

Table 2.2: This table presents the selected and analyzed VBS examples, focusing on the VBS means from the left side of the curated VBS design space (see Figure 2.2). Each row represents a distinct VBS example, while columns delineate various design dimensions. A (✓) icon within a cell indicates that the corresponding VBS example exhibits the specified characteristic or feature. The coded VBS examples are available in an interactive survey browser under `https://intavia.github.io/`.

	Entity-orientation					Story Complexity						Story Schemata										Plot Patterns								Story Arc & Hook					Linear		Factuality				Other
Name	Objects	Persons	Sets	Events	Places	Synchronic: Simple	Synchronic: Medium	Synchronic: Complex	Diachronic: Simple	Diachronic: Medium	Diachronic: Complex	Actor Biography	Object Biography	Place Biography	Hybrid Biography	Biography Sequences	Biography Bundles	Inverted Trees	Trees	Larger Topic / Era	Larger Topic / Multi-era	Genesis Plot	Emergence Plot	Destruction Plot	Metamorphosis Plot	Cause & Effect	Convergence	Divergence	Oscillation	Set-up	Rising Conflict / Supporting Facts	Climax / Main Insight	Resolution / Conclusion	Story Hook	Linear Storytelling	Non-linear Storytelling	Factuality	Uncertainty	Fictious Elements	Fictious Story World	Gamification Elements
"Wer heilt hat recht": Ein Aus... [170]	✓	✓	✓	✓	✓			✓			✓	✓	✓	✓							✓		✓							✓	✓		✓	✓	✓		✓				
An Infamous Day [112]	✓	✓		✓	✓			✓		✓					✓		✓							✓		✓	✓			✓	✓	✓	✓		✓		✓				
Archaeology of Wine [349]	✓						✓				✓		✓							✓																✓					
Are men singing higher in pop ... [286]	✓	✓						✓		✓					✓	✓							✓							✓	✓	✓	✓	✓	✓		✓				
Around the Globe with Reinhold... [124]		✓		✓	✓	✓				✓		✓											✓													✓					
Daily Life In The Middle Ages [140]	✓							✓			✓									✓										✓	✓			✓	✓		✓				
Dante's Inferno [210]					✓	✓			✓					✓								✓								✓	✓				✓		✓		✓		
Game of Throne Arya's Jouney [233]		✓			✓	✓				✓		✓													✓										✓				✓	✓	
History of Whitney Houston [237]		✓				✓				✓		✓										✓								✓	✓	✓		✓	✓		✓				
How Wine Colonized The World [437]	✓				✓			✓			✓										✓				✓					✓	✓			✓	✓		✓				
How You Play Spades is How You... [135]				✓				✓		✓										✓										✓	✓					✓	✓				
January 1969: Mapping the Sit-... [35]		✓		✓		✓				✓										✓			✓			✓			✓	✓	✓	✓	✓			✓	✓				
Justice Deferred - Executive ... [114]		✓		✓	✓			✓			✓				✓		✓				✓	✓	✓		✓	✓				✓	✓	✓	✓	✓	✓		✓				
Kosmos Kaffee [126]	✓					✓			✓				✓										✓			✓				✓	✓	✓	✓		✓		✓				✓
Major Battles in the Napoleoni... [13]				✓	✓		✓			✓										✓																	✓				
Map Shows How Humans Migrated ... [186]		✓		✓				✓	✓												✓		✓		✓					✓	✓	✓	✓	✓	✓		✓	✓			
Mapping the "White, Marmorean ... [315]		✓			✓	✓			✓			✓											✓		✓					✓	✓	✓	✓		✓		✓				
Mapping the Catalogue of Ships [385]					✓	✓			✓				✓																	✓				✓	✓		✓		✓		
Medieval Philosophers [423]		✓			✓		✓		✓								✓																			✓	✓				
Mercator: It's a flat, flat wo... [99]	✓	✓				✓				✓		✓	✓							✓			✓			✓				✓	✓	✓	✓			✓	✓				
Miles Davis' Famous Albums [227]	✓	✓	✓			✓				✓					✓							✓								✓	✓	✓	✓	✓	✓		✓				
Objects of Wonder [402]	✓		✓				✓			✓			✓				✓			✓		✓	✓		✓	✓				✓	✓	✓	✓		✓		✓				
Patterns in the life of Vincen... [403]	✓	✓	✓					✓		✓		✓	✓		✓								✓							✓	✓	✓	✓		✓		✓				
Slave Revolt in Jamaica, 1760-... [53]				✓			✓				✓									✓						✓			✓	✓	✓	✓	✓		✓		✓				
Southern Literary Trail [138]	✓	✓			✓		✓		✓						✓	✓														✓				✓	✓		✓				
The Fallen of World War II [160]			✓	✓				✓			✓									✓					✓					✓	✓	✓	✓	✓		✓	✓				
The Giant Squid: When Myth Enc... [143]	✓				✓			✓		✓			✓			✓				✓			✓							✓	✓			✓	✓		✓				
The Life of Mary Kearn [285]	✓	✓		✓		✓					✓	✓	✓		✓								✓													✓	✓				
The Travels of Marco Polo | Na... [**MarcoPolo**]		✓				✓			✓			✓											✓		✓	✓				✓	✓	✓	✓	✓	✓		✓				
US Westward Expansion [325]					✓			✓			✓										✓	✓								✓	✓				✓		✓				
Virtulleum, Tulln [128]	✓	✓		✓	✓		✓		✓			✓	✓	✓					✓		✓	✓	✓											✓		✓	✓		✓		✓
Visualization-based Scrollytel... [**MusEcologyScrollytelling**]	✓		✓		✓		✓			✓			✓	✓						✓					✓	✓				✓	✓	✓	✓		✓		✓				
When Napoleon Ventured East [321]	✓	✓	✓	✓	✓			✓		✓					✓					✓				✓		✓	✓			✓	✓	✓	✓	✓	✓		✓				
Wonky [304]	✓					✓			✓				✓									✓	✓		✓					✓	✓	✓	✓	✓	✓		✓				✓

Table 2.3: This table is a continuation of Table Table 2.2. It delves into the VBS presentation aspects of the analyzed VBS examples, reflecting the right side of the curated VBS design space (see Figure 2.2). Each row represents a VBS example, with columns representing different design dimensions. A checkmark icon (✓) in the table cell signifies the VBS example's possession of the associated characteristic or feature. The coded VBS examples are available in an interactive survey browser under `https://intavia.github.io/`.

2.2.7 Unique VBS Examples

We have already referred to various VBS examples when introducing the categories of our design space in Subsection 2.2.5. Looking at the whole sample, the focus shifts to aggregating these observations to identify overarching trends, commonalities, and interconnected facets within the larger VBS landscape for the DH and CH domains. It is crucial to point out that our collection of VBS examples is intentionally diverse and is not intended to be exhaustive—following a topic-centered survey and research design, as we discussed in Subsection 2.2.4. By contrast, we selected and curated a sample of 34 unique VBS designs from the whole analyzed corpus to provide an overview of contemporary trends and best practices of VBS in DH and CH here in detail. These emergent trends and gaps can offer valuable insights into the foundational principles and creative possibilities inherent to VBS in the DH and CH domains, thereby enhancing its efficacy as a tool for conveying informative, engaging, and immersive stories.

Categorization & Analysis

From the trends and gaps observed in the analysis of Table 2.2 and Table 2.3 various high-level observations and insights can be extracted:

User Accessibility & Engagement: The dominance of texts and images as the main media types, along with the prevalent use of scrollytelling and the focus on desktop and mobile devices align with a general design philosophy aimed at maximizing accessibility and user engagement. In contrast, audio and film are typically more immersive media types, but require more time and attention by recipients, which reduces accessibility of VBS in comparison to text and images, but could significantly enrich the storytelling experience in cultural and historical contexts. Furthermore, the frequent incorporation of design features like story hooks in VBS offers a unique opportunity to capture the audiences attention, drawing them into the narrative world and engaging their cognitive faculties in the future.

Simplification & Intuitiveness: Timeline- and map-based visualizations are the most widely used visualization types by the VBS examples of our sample—perhaps because they are intuitive and reduce cognitive load, as they are familiar to most story creators and recipients. The aim to make VBS within the CH and DH domain simple and reduce cognitive load, is also reflected in the frequent use of textual narratives and in-text references to guide the recipient through the story. Simplicity extends to entity orientation and story complexity, where even highly complex stories revolving around larger sets of entities (such as [186], which breaks down how humankind spread throughout Earth) are broken into a sequence of more digestible information units. This reflects a preference for simplicity and familiarity, facilitating user comprehension. While this approach aids in reducing cognitive load, it often simplifies complex cultural and historical narratives, holding the threat of oversimplifying intricate stories and historical nuances.

Narrative Structure & Content: The story thread predominantly features a textual narrative combined with elements of temporal succession or moving camera effects, reflecting the human preference for linear, easy-to-follow stories. The frequent choice of story schemata like "genesis" and "emergence" for specific topics further supports this, indicating a dominance of simpler developments in contrast to, e.g., "destruction", "divergence", and "oscillation" plots, which imply more complex changes over time. The dominant linear and textual narrative structures, though appealing for their clarity and ease of follow, may not adequately capture the complexity and multifaceted nature of stories in DH and CH. This trend highlights a gap in utilizing more complex narrative schemas, like non-linear or multi-threaded plots, which could offer a richer, more nuanced portrayal.

Analytical Depth & Factual Orientation: Our sample of VBS examples shows that VBS tends to focus on factual, real-world stories, often employing "cause & effect" narratives when dealing with broader topics. This reveals an expectation for VBS to serve educational or informational purposes rather than pure entertainment purposes, as fictional or uncertain elements are used to a lesser degree. However, this emphasis sometimes sidelines the creative and interpretative aspects of storytelling, which are vital in exploring and representing cultural histories and heritage.

Innovation & Experimental Approaches: Although rare, the use of gamification, augmented reality, and 3D renderings indicates an increasing interest in experimental immersive VBS techniques. However, these are not yet mainstream, suggesting that the field is still testing how these more complex elements can fit into a format, which is accessible to a broader audience. Certainly there is a notable opportunity here for broader and more innovative applications of these technologies to create more immersive and interactive storytelling experiences in the context of CH and DH.

The categorization of our observed trends and gaps brings VBS practices into a broader perspective. We thus get a more integrated view that reveals a VBS landscape focused on accessibility, cognitive ease, linearly structured narratives, factual representation, and cautious innovation, despite of our documented range of increasingly advanced and complex design options.

Highlighted Examples

In the following we feature specific VBS examples for the purpose of contextualizing these within the broader themes identified in our earlier analysis. This serves to bridge theory with practice and by highlighting how specific design dimensions but also overarching concepts manifest in actual VBS examples. Specifically, we highlight how certain examples use the design dimensions of our design space and embody one or more of the high-level themes we uncovered previously.

"Southern Literary Trail" is a collaborative project involving encyclopedias from Alabama, Mississippi, and New Georgia in the southern US, telling the stories of 27 authors from the 20th century. As a prototypical example of Knight Lab's StoryMapJS [235], the path through the three US states is mapped onto a historical map of the US (see Figure 2.13). Twenty-four cities that shaped the writers' lives are examined on the Southern literary trail, and special places in towns are additionally highlighted with photographs when they inspired the authors or are closely related to them. The time is not of importance throughout the trail. Instead, the path is made by panning from one place on the map to the next in a slideshow. The textual annotations connect the places

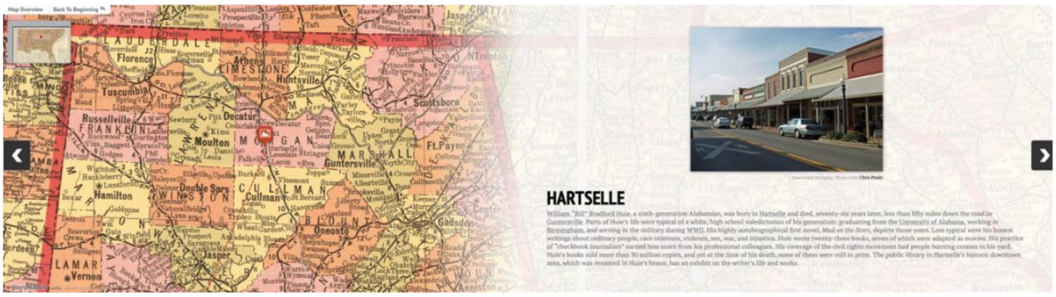

Figure 2.13: Southern Literary Trail and the writers' stories around Hartselle where for example William Bradford Huie was born in 1910 (source: `https://georgiahumanities.org/southern-literary-trail-story-map/`).

with the writers' lives, careers, and objects they created (in the form of lists of their works) and links to further external sources. Although the path on the map is linear and author-driven due to the slideshow story layout, the users are still allowed to zoom and pan using the map and to create their own routes by clicking on the highlighted and mapped places. This aspect brings forth questions about user agency in digital narratives and the balance between curated content and user-driven exploration. The project thus serves as a case study for exploring how digital tools can enhance engagement with CH while also presenting ongoing challenges in these fields. An other significant research question in DH is the representation and interpretation of spatial and temporal data, as seen here where the time is not of primary importance, raising questions about the non-linear nature of history and narrative and how digital tools can best represent this complexity.

Miles Davis' Famous Albums is a DataToon data comic [228], which links actors and objects in CH. The narrative about the accumulation of instruments used in recorded albums by Miles Davis is represented through juxtaposed network graphs, presented in a comic strip format with distinct panels for various albums or timeframes. The narrative thread is thereby given through the progression throughout the time and changes along the panels. Graph nodes represent individuals (singers, musicians) and objects (albums or instruments), connected by edges indicating the relationships, specifically showing which instruments were used in which album production. Due to its static nature the comic lacks interactivity (see Figure 2.14). This shortcoming prompts questions about user engagement and the potential for dynamic, interactive storytelling methods in digital humanities and highlights the challenge of integrating interactivity in data narratives. This approach to display everything at once also brings to the forefront ongoing research questions in DH and CH about how to effectively combine quantitative data with qualitative narrative, about the interpretation and accessibility of complex data through storytelling and visual representation and underscores the challenge of depicting temporal and relational dynamics within a static visual medium. How can static representations maintain the fluidity and evolution of cultural and musical phenomena, such as the progression of Miles Davis' career and his changing relationships with various instruments and collaborators?

Figure 2.14: Data comic on famous albums of Miles Davis and the featured musical instruments (source: https://datatoon.github.io/examples/milesdavis.png).

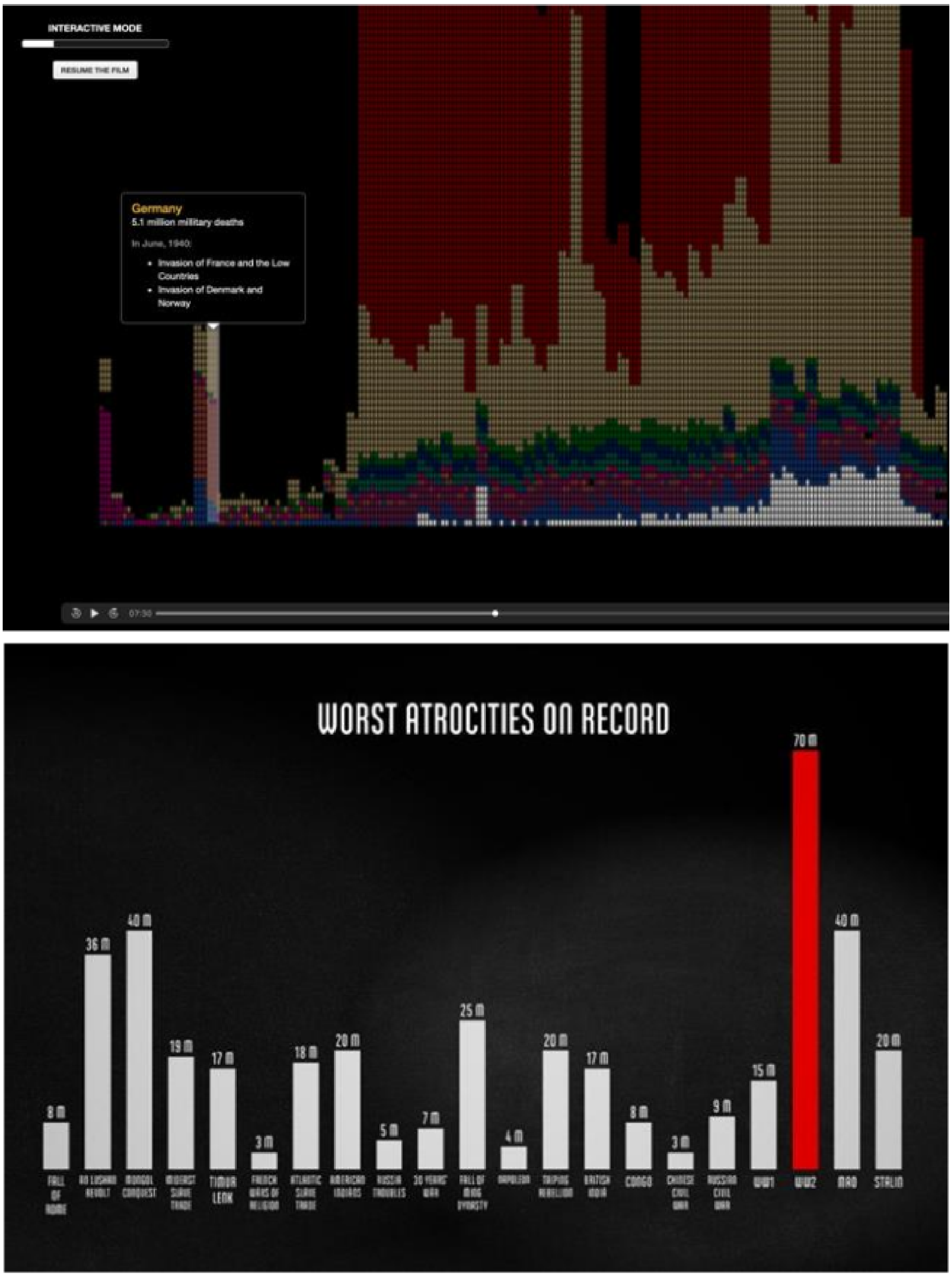

Figure 2.15: The Fallen of World War II, with an interactive visualization component (top), and a contextual largescale visualization of the human history of violence (bottom).

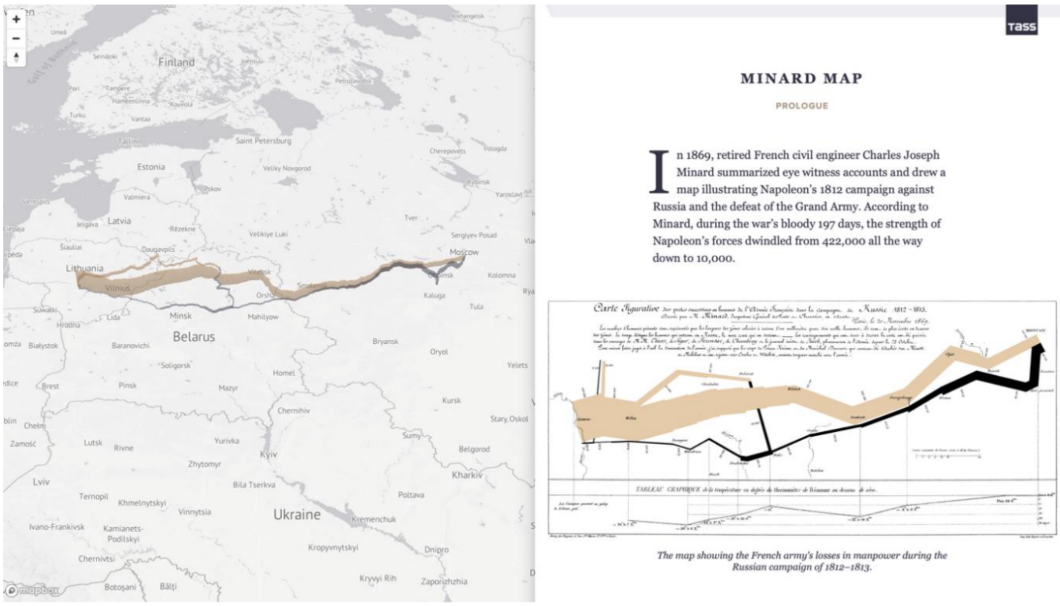

Figure 2.16: Minard's map—as implemented by the TASS Infographics studio in 2017 (source: https://1812.tass.ru/en).

The Fallen of World War II by Neil Halloran is a data-driven documentary presented in video format with timelines and charts (see Figure 2.15). It undertakes a comprehensive analysis of the larger topic of World War II's impact. The video employs Isotype-like pictographs, using a symbol to represent a thousand casualties, to recapitulate and compare the war's casualties, encompassing soldiers and civilians from various countries. Casualty symbols are arranged in waffle or bar charts, organized by country, time, or specific attributes. The narrative employs audio narration, animated diagram development, and camera movement to create immersive storytelling and evoke narrative tension. For instance, the camera slowly ascending a stack of symbols vividly conveys the magnitude of casualties. Twice in the 18-minute video, interactivity is introduced, allowing viewers to pause and explore overview charts in greater detail, enhancing their understanding of the data analysis. This feature brings to light questions about user agency in digital narratives, the balance between linear storytelling and interactive exploration, and how interactivity can enhance viewers' understanding and engagement with complex historical data. This project alos exemplifies the challenge of presenting large-scale, complex data (such as casualty figures) in a way that is both comprehensible and respectful to the subject matter. The casualty symbols, arranged in waffle or bar charts and organized by country, time, or specific attributes, highlight the research question in DH of how to visually narrate historical data without oversimplifying or trivializing the human experiences behind the numbers. The narrative, enhanced by audio narration, animated diagram development, and camera movement, showcases how digital storytelling can create immersive experiences. The technique of the camera slowly ascending a stack of symbols to convey the magnitude of casualties is a poignant example of visual storytelling.

When Napoleon Ventured East is an interactive story based on Charles Joseph Minard (1896) renowned visualization detailing Napoleon's 1812 war campaign against Russia, which has become one of history's most referenced visualizations. The static drawing maps the French Grand Army's journey from Lithuania to Moscow and back, with the lines' width conveying troop strength. Despite Napoleon's initial superiority and expectations of a swift victory, the massive army struggled with logistical challenges, famine, and summer heat, leading to a different outcome. The visualization has been transformed into an interactive map-based narrative using scrollytelling (see Figure 2.16), with accompanying text, images and charts placed alongside it. This narrative format elucidates significant events occurring in time and space, such as river crossings, strategic army divisions, war declarations, and clashes. The story's progression triggers corresponding animations on the map. The text is enhanced by portraits and quotes from key figures like Napoleon and Alexander I, as well as their commanders and soldiers. Additional statistical visualizations provide insights into Russian and French troops and artillery, while an aligned line chart highlights temperature variations as environmental threats. The interactive online version also covers the French army's return journey during the harsh winter months. This approach raises crucial research questions in DH. How can interactive digital tools, like scrollytelling, enhance the understanding of complex historical events? The story's progression, triggering corresponding animations on the map, is not just a technical achievement but also a methodological challenge in DH, blending historical accuracy with engaging storytelling. Furthermore the text, enhanced by portraits and quotes from key figures like Napoleon and Alexander I, as well as their commanders and soldiers, reflects the ongoing challenge of integrating diverse types of historical sources into a cohesive narrative. This approach also raises questions about representing multiple perspectives and experiences in historical narratives. Ultimately the inclusion of these elements prompts questions about the role of environmental data in historical narratives and how they impact the interpretation of events.

Virtulleum tells the story of the history of the city of Tulln (Austria) via spatial positioning of museum objects on an interactive city map. However, these points of interest are also located within specific "times of interest" within the city's history, culminating in the museum object. To avoid overlaps, the mobile storytelling experience does not show all objects on a city map but generates a random selection (users throw real dice) of objects distributed along the main time periods of the city's history. This breaks linear and causally connected storytelling into multiple story chunks orchestrated by space, time distribution, and chance. These story chunks enable free exploration of multiple interactive experiences, like quizzes, mini-games, augmented reality, 3D representations, 360° views, or time panoramas (see Figure 2.17). This approach brings to light significant DH challenges, such as how to represent the complex interplay of time and space in historical narratives effectively. The implementation of dices as real-world item raises important research questions in DH: How does the introduction of randomness and non-linearity affect the user's understanding and engagement with historical narratives? How does augmented reality enhance or alter the perception of historical artifacts and sites? What is the role of gamification in historical learning and engagement? How can 3D representations and 360° views contribute to a deeper understanding of historical contexts?

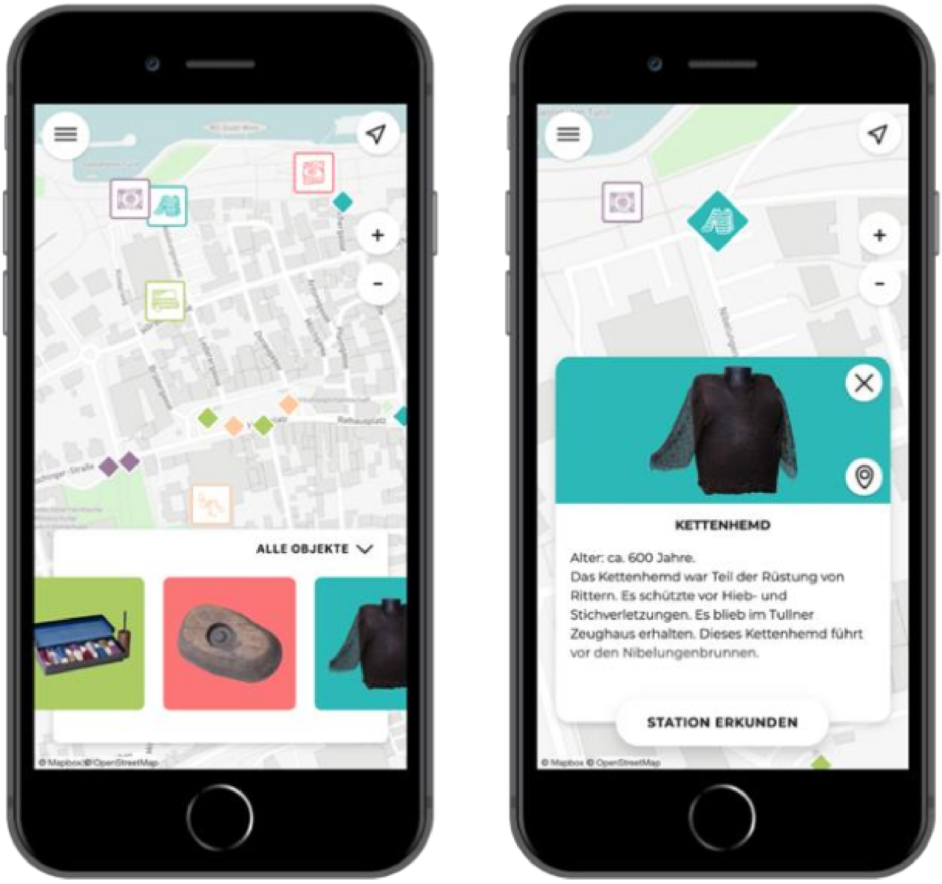

Figure 2.17: Virtulleum: Points of interest on interactive map reveal rich media objects, Video: `https://youtu.be/nPvFvfXV8h0`. Photo: © Fluxguide.

2.2.8 Conclusion & Future Challenges

With this topic-centered review of VBS literature, research, and practice we analyzed a wide variety of tools and unique examples addressing the topic of VBS within DH and CH from different angles. By doing so we aimed to deliberately bridge theoretical reflections and reports on current state of the art-designs with practical solutions for story creation to support scholars and practitioners in DH and CH fields. To synthesize a topic-centered design space for this emergent trading zone we investigated existing VBS design spaces and augmented them with features and categories not discussed in previous works. The ensuing analysis of unique VBS examples and tools spells out the current distribution of research, development and available applications in this complex concept and technology space for the first time. It shows both dominant approaches and trends, together with design and implementation gaps, but also confirms the potential of advanced VBS concepts—such as story schemata, plot patterns, or narrative (un)certainty—which are largely unexplored within DH and CH fields until now.

The investigation also uncovered several open challenges. Among those, we consider the use of augmented reality (AR), storytelling with micro-content and gamification, and set and graph visualization as important areas of future development—together with several other conceptual and technological challenges.

Mixed Reality Designs Augmented Reality (AR) is used in industry to visualize complex data and facilitate data-driven processes, making it possible to analyze data in three dimensions and place different data outputs next to physical reference objects [284]. Digital information can be displayed directly in the visitors' fields of vision and controlled via touch, gestures, or speech, depending on the selected target device.

For cultural institutions, AR creates the possibility of linking complex cultural data with real-world CH objects in the physical spaces of DH and CH institutions (such as galleries, libraries, archives, museums, but also in environments of cultural tourism, education, or academia) and to offer new ways to create narrative connections between objects, related actors, places, and historical events, which are otherwise challenging to present. Museums, however, have only begun to exploit this potential [392]. Augmented visualizations can tell visualization-based stories relying on metadata and additional information on cultural objects (cp. [36]): For example, they can guide users through an exhibition by augmenting objects with a temporal storyline shown on a mobile device. They could also blend in timelines on important events and persons related to an object, show networks between persons depicted in a painting, or similar. While this augmented VBS design space has yet to be explored in more detail, we consider it to be key for the essential linkage of digital and physical CH spaces. This seems of particular relevance for existing CH institutions and places dedicated to the mediation of DH topics, which often fear to be replaced by the emerging digital "mirror world" [215]. In this context, "post-digital" VBS solutions (i.e., hybrid design strategies deliberately mixing the best of digital and physical worlds) can help to strengthen the attraction power of countless CH institutions struggling to pursue their cultural and societal mission [367, 458].

Storytelling with Micro-Content and Gamification Knowledge communication in CH institutions such as museums is often understood as academic text production and presentation instead of creative storytelling. Based on positive experiences from the field, we consider the use of a storytelling concept relevant that consists of individual "micro-content" building blocks [128]. This concept has been established in e-learning as "microlearning" and enables content to be conveyed in an entertaining and meaningful way, especially on mobile devices. Related designs avoid to present the content for a CH tour or point of interest in a museum as long-form texts or audios but along an interactive narrative, which consists of micro-units ("experience blocks" or "micro-content chunks") like short audio clips, pictures, videos and animations, short texts, interactive visualizations, or gamification elements. The recipients can freely explore the individual, interrelated experience blocks, depending on their interests, contexts, and prior experiences. Recent developments in the field of artificial intelligence will allow to causally link these micro-contents and generate individual stories on the flow [26, 117].

Storytelling gains dynamism by also defining interactive tasks as experience blocks. This leads to a deepened involvement and additional activation of the users: The cultural content is not passively consumed but also actively applied directly after the introduction. Users are encouraged to

Author-driven design
– Creating diversified opinions is not supported
– Strict story design hampers user engagement
– Amount of information limited to story
+ Expert story conveys intended message
+ Single story path is easy to evaluate
+ Minor risk of interaction fatigue
Reader-driven design
– A particular story is hard to convey
– Hard to evaluate due to multiple story paths
– Interaction fatigue may occur
+ Interaction facilitates individualized opinions
+ Interaction supports user engagement
+ High amount of information reachable

Table 2.4: The strengths and limitations of author vs. reader-driven storytelling design [391].

think about the content. Solving interactive tasks should be accompanied by direct feedback (see [393]). As part of the micro-content storytelling strategy, gamification involves using games to leverage user experience and their engagement and motivation for services and applications outside the traditional game genre. They are used there to make learning more interactive, encourage active participation and personal reflection via the mental involvement of learners, and reduce mental digression.

Utilizing Set and Graph Visualizations During our analysis, we encountered only a limited number of VBS instances where set and graph visualizations serve as the foundational elements of storytelling. Similarly, not too many VBS tools allow to create stories based on these visualization types. However, it is imperative to recognize that VBS with set and graph visualizations hold immense potential and promise. As data sets become increasingly multi-modal, linked, complex, and interwoven, comprising a wide variety of entities and their intricate relationships, the stage is set for the emergence of novel VBS approaches based on graph and set visualizations.

Balancing Reader- and Author-Driven Designs Visualization-based stories can provide their readers with different degrees of freedom to interact within the story and to explore different interpretations and perspectives. As pointed out repeatedly, Segel and Heer [391] classified stories on a range from being a well-prepared narrative by the author ("author-driven") to being a rather interactive visual analysis system ("reader-driven") that allows users to generate individualized perspectives of the story world. Many exciting combinations across the two approaches exist, bearing various trade-offs regarding user engagement (see Table 2.4). In our analysis of VBS examples within the DH and CH domains, we observed a tendency towards more author-driven stories with only limited exploration options. A few exceptions which also offer more exploratory features [253, 403, 415] show the potential for richer, more engaging stories, which offer a higher degree of freedom to story recipients. We consider this area to be a promising field for future developments, but also user studies—and for related learnings with relevance for many other VBS application areas.

Lack of Object-Oriented Storytelling The review of VBS examples has revealed that only a few examples focus on single objects or object collections. In other words, until now, only a few stories have been developed to convey the "biographies of things" [161], which have become an established genre in cultural studies or in art history such as the "Mapping Titian" project [75], are rare exceptions. However, both are restricted to a particular object or set of objects, and neither uses sophisticated storytelling techniques.

Guidance, Exploration, or Storytelling The analysis of VBS examples shows that use cases differ with respect to the extent that they include the classical elements of a story, as presented in Subsection 2.2.2. Several examples have been excluded due to a missing narrative. Other examples guide linearly through (visual) historical material or allow for open-ended exploration of the (visual) information. A narrative arc, i.e., a progressive increase of tension towards a climax followed by a resolution, and a narrative hook, i.e., a problem or fact that raises interest and captures the audience's attention, are often missing in what is presented as "story" in the DH and CH domain. Therefore, we see a need for a more apparent distinction of VBS concepts from related concepts like guidance [63] and open-ended explorative visualizations [458]. Further research is also needed to study whether a narrative hook and a narrative arc (or visual design elements in different phases of it – cp. [469]) can raise recipients' interest and prolong the interaction with a VBS instance.

Critical Reflection vs. Narrative Information Processing DH and CH topics arguably should not be processed in an isolated way but critically interpreted and reflected in the context of their historical period and their socio-cultural context. By contrast, information in stories has shown to be mainly checked for plausibility and coherence—but to be less critically analyzed or reflected (see [54, 60]). This is a particular issue for the use of storytelling in DH and CH domains, where the critical reflection and evaluation of semantic and cultural materials is widely seen as the core objective of every inquiry [272, 458]. Therefore, we consider it a substantial but fascinating challenge for VBS to develop visualization approaches facilitating reflection and critical reasoning (see [78, 101]) with storytelling—especially in domains like CH and DH.

Science Communication and "Popularization" vs. Oversimplification From a science communication perspective, storytelling techniques are frequently recommended and used in places where there is reason to believe that complicated, academic prose is not the most effective or ideal way to address, attract, impress, and engage non-expert audiences. Similarly, storytelling designs appear attractive from a visualization perspective, where visualizations have limitations (cp. Table 2.4) or might be too complex or opaque for non-expert audiences to convey central messages 'by themselves'. However, there is a delicate balance or trade-off to be found for all situations where public communication of scholarly content (frequently already negatively referred to as "popularization" endeavors) takes place, as critics admonish the possible adverse effects of "oversimplification". A balancing example is [143], where a popularized VBS story is combined with scientific references.

Visualization and Storytelling Rhetorics Similar to the risks of oversimplification, we are aware of heightened *rhetorical effects*, which are inevitable byproducts of visualization and communication endeavors in general [179, 324] and which could be technically also aggravated with the enhanced involvement and engagement techniques of advanced VBS designs. In their analysis, Hullman and Diakopoulos [179] investigated such effects, mainly concerning the framing of visualizations, i.e., how an author's design choices, experience, and identity and a reader's cultural, individual, and perceptual constraints may influence the interpretation of a visualization-based story's message. An example is the story of the attack on Pearl Harbor [112], which is told predominantly from an American perspective. Editorial layers capture design decisions regarding visualization and narration techniques used in creating visualization-based stories, which can manifest at different levels.

As becomes evident in such reflections, VBS offers novel means for DH and CH scholars and professionals to reach and engage a wide range of audiences in an increasingly datafied society [433]. DH and CH, on the other hand, constitute highly challenging but rewarding application fields for visualization and media designers. We consider their unique constellations of data, users, tasks to pose a range of unique challenges, that significantly enriches the existing spectrum of challenges and solutions for the visualization and VBS community. With increased mutual understanding, there is reason to expect novel exchanges, co-designs, and innovation on all sides.

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3 Musical Instruments and Musical Pieces

"Where words fail, music speaks."
– Hans Christian Andersen

3.1 Overview & Contributions

Music, akin to the written word, possesses the unparalleled ability to evoke emotions profoundly and universally, transcending the need for explicit narratives or spoken language. Celebrated poet Henry Wadsworth Longfellow once remarked, *"Music is the universal language of mankind"* [275], underscoring its power to communicate across cultural and linguistic barriers.

This universal language is articulated through the interplay of musical instruments and musical pieces, whether meticulously composed or spontaneously improvised music. At the heart of music's impact is its interpretation, a process to which life is breathed through people. Yet it is shrouded in mystery, especially concerning the historical contexts of performances. Arousing questions such as *"What pieces were performed, when, and on which specific instruments and by whom?"*.

To unravel those hidden stories of musical artifacts again digitization and data visualizations are going to be developed and used in the journey of the following two papers [250, 252]. These two papers showcase the incompatibility of different historical vocabularies during the search of finding parameterized similarity measures, acting as heuristics for hypotheses of unseen (cor)relations between particular musical instruments and musical compositions based on their metainformation such as manufacturing or performance dates and locations.

Musicology, and specifically its sub-branch of organology, delves deep into the study of musical instruments — their construction, history, and provenance. Musical instruments and compositions represent tangible threads of our cultural heritage, intertwined with the intangible traditions of music performance and instrument crafting. One challenge within this field is the lack of detailed knowledge regarding the specific musical pieces performed on historical instruments. This inquiry into the relationship between instruments and compositions confronts the incompatibility of historical vocabularies, necessitating parameterized similarity measures as heuristics to hypothesize potential correlations.

While musicology encompasses various entities — persons such as composers, musicians, publishers, and instrument makers — the majority of this rich tapestry is digitized as metadata. The advent of multimedia digitization across cultural heritage domains, facilitated by technologies such as (3D) scanning, photogrammetry, drones, or computed tomography, has revolutionized the preservation and study of tangible artifacts. In the realm of musical instruments, these technologies not only enable sound recording and the measurement of physical attributes for virtual reconstruction but also pave the way for exploring the instruments' historical and cultural significances. Musical pieces on the other side, now available in multimedia formats beyond mere notes, are supplemented with extensive metadata, including details on composers, performers, and the historical context of performances. However, the (digitized) information on musical instruments often suffers from sparsity, limited to initial performances or the creation events of the instruments themselves.

Despite the wealth of digitized entities and their metadata housed in various repositories, the sheer volume and complexity of this data necessitate computational analysis to bring these artifacts into context. Musical instruments, integral to historical ecosystems influenced by institutions, orchestras, and commissioned production, require interactive and engaging methods to be fully appreciated. Virtual exhibitions offer a solution to the limitations of physical space (e.g. in museums), allowing for a broader exposure of these cultural treasures around the globe.

However, the task of contextualizing musical instruments and pieces within their historical and changing ecosystems is compounded by the disparate modeling of related entities across databases. For example geographical information often are represented merely as text, lacking the exact coordinates, needed for a geo-spatial mapping. An other instance of such ambiguity are the varieties of languages and concepts, such as given by the terminologoy for musical instruments or genres. Both are still exposed to threat to be changed throughout the times, as borders might move and meanings of terms change. Bridging these gaps requires innovative approaches to model or match entities across databases, enhancing our understanding of cultural heritage and striding against the partitioning within silos.

Assessing and visualizing those hidden relationships between musical instruments, compositions, and their historical contexts require innovative representation strategies. These include visual encodings of entity proximity, links, instrumentation, and geospatial information, enhanced by approaches like semantic zoom to navigate the complex landscape of musicology. Through such enabled visual analytics, we can begin to unravel the intricate web of connections that defines our musical heritage, offering new insights into the universal language of music.

We are also going to touch on the musical instruments' biographies themselves, since they can last over decades and they might have been constantly modified or restored. Throughout the presented use cases of specific instrument or instrument group stories it will become clear that high valued instruments were not only commissioned and created but also kept updated to trends and new movements in the music culture and that they were highly embedded in the surrounding socio-cultural ecosystems.

This chapter is based on two papers that build on each other.

Paper 2: **A Timeline Metaphor for Analyzing the Relationships between Musical Instruments and Musical Pieces** [252] is introducing the methodology of finding and assessing of alignments of musical instruments and musical compositions, which is then visualized by a problem-specific timeline and map design.

The subsequent Paper 3: **Visualizing the Aura of Musical Instruments** [250] enhances this approach by the further "auralization" within one interactive tag-cloud and by additional interaction techniques. The collective contributions of them can be summarized as:

1. **Assigning Compositions to Instruments**: The project developed similarity measures based on instruments and performances' geospatial, temporal, and descriptive attributes, aligning with musicological concepts to suggest possible matches.
2. **Auralization System**: An interactive visual analytics system allows musicologists to evaluate hypothesized pairings between compositions and instruments, aiding in forming a comprehensive understanding or "aura" of specific instruments or types.
3. **Timeline Metaphor**: A novel explorative analysis tool visualizes the relationship between instruments and performances over time, integrating additional views to support or contest automated matching suggestions.
4. **Visual Encoding for Uncertainty**: The system visually represents temporal uncertainties and the likelihood of matches within the timeline view to prevent misinterpretation.
5. **Semantic Zoom**: A customized approach to semantic zooming supports both broad and detailed investigations, catering to various research interests.
6. **"Aura" Tag Cloud:** A significant enhancement by the second paper [250] is the introduction of an "aura" view for one or multiple instruments. This aura is visualized as a tag cloud that aggregates descriptive words from matched musical pieces, where the arrangement is determined by a force-directed graph drawing algorithm. This visualization includes images or placeholders for instruments at the center, with words representing four attributes of musical works and instrument titles. The words appear in five different colors, aiding in the quick visual identification of the instrument's aura.
7. **Use Cases**: Make it ore tangible and show the usage and work with the tool. Two specific use cases are detailed "The Protestant Trombone" and "Lutes and Lute-like Instruments" —demonstrating how the system can be used to explore the musical and historical context of specific instruments through the visualization of matched pieces, genres, composers, and other attributes within a geographical and temporal scope.
8. **Enhancements** to the interactive selection and exploration features within the visualization system, facilitating a deeper and more user-friendly analysis.

Utility & Future Work The system demonstrates practical utility for musicologists by offering diverse usage scenarios, from generating hypotheses for auralization tasks to exploring instrument careers and cultural contexts. The interdisciplinary collaboration highlights the potential for digital humanities to uncover new insights into musicology, supported by innovative visual analytics and interaction designs. The project outlines avenues for improving the similarity measures, incorporating additional data sources, and enhancing the visual analytics system to support more complex queries and explorations. It is still apparent that there is a need for external domain knowledge and stories to actually make sense out of some of the visualized information. Practical application suggestions for using the visualization system in museum contexts to enrich visitor experiences by contextualizing historical musical instruments through their associated musical pieces and histories.

3.2 Paper 2: A Timeline Metaphor for Analyzing the Relationships between Musical Instruments and Musical Pieces

Jakob Kusnick[1], Richard Khulusi[2], Josef Focht[3] and Stefan Jänicke[1]

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[2] Image and Signal Processing Group, Institute for Computer Science, Leipzig University, Leipzig, Germany
[3] Musical Instrument Museum, Institute for Musicology, Leipzig University, Leipzig, Germany

Abstract: *Digitization projects make cultural heritage data sustainably available. However, while digital libraries may capture various aspects, relations across different sources often remain unobserved. In our project, musicologists aimed to relate musical instruments with historical performances of musical pieces, both contained in different sources. We defined a similarity measure taking instrumentation, temporal as well as geospatial metadata into account, with which we were able to hypothesize potential relations. We propose a novel timeline design that offers a specific semantic zoom metaphor enabling the collaborating musicologists to observe and evaluate the results of our similarity analysis. The value of our system for research in musicology is documented in three case studies.*

3.2.1 Introduction

In musical instrument museums, we encounter historical musical instruments or musical instruments from around the world [88]. Instruments are typically arranged in glass showcases or separate subdivisions, only a few instruments can be played in sound laboratories or heard during performances. In rather modern, global collections, as offered by the Musical Instrument Museum (MIM)[1] in Phoenix, Arizona (United States), the exhibition is further enriched with video and sound material from performances conveying sound and functionality of instruments. However, in historical collections, such enrichments can hardly be offered. This is caused by most instruments not having recording data and the instruments not being in a playable condition without risking to damage or destroy the rare or unique items. Further, even musicologists sometimes wonder in which particular composition's performances a historical music instrument was used. The musicological term *auralization* describes this research interest of framing an instrument with related compositions in order to picture its career and to facilitate forming "a mental impression of a sound not yet heard" [409].

Past digitization endeavors provide exhaustive digital collections of musical instruments and performances alike. On the one hand, the "Musical Instruments Museum Online" (MIMO)[2] provides structured information about around 65,000 music instruments, while, on the other hand, the "Répertoire International des Sources Musicales" (RISM)[3] holds a database with information about more than 1,100,000 musical pieces. By matching instrument types, taking geospatial as well as temporal constraints into account, we combined both data sources that prepared

[1] https://mim.org
[2] https://www.mimo-international.com/MIMO/
[3] https://opac.rism.info/

the ground to support generating hypotheses for the auralization of music instruments by quantitative, computational means. This paper outlines our interdisciplinary collaboration involving both visualization scholars and musicologists for the development of an interactive visual timeline environment supporting the musicologists' auralization task. In summary, our contributions to the visualization community are:

- **Assigning compositions to instruments**: For various geospatial, temporal and descriptive attributes of instruments and performances, we designed similarity measures that reflect the likeliness of a composition being played with an instrument in accordance to musicological conceptions.

- **Auralization system**: We designed a visual analytics system that is used by musicologists to interactively evaluate hypothesized matchings of compositions and instruments, supporting to gradually form the *aura* of a particular instrument or instrument types.

- **A novel timeline metaphor**: We propose a timeline metaphor for the explorative analysis of instrument/performance matches that are exposed in a historical frame. Additional views can be consulted to foster or refute automatized matching suggestions.

- **Visual encoding for uncertainty**: Within the timeline view, we reflect temporal uncertainties for instrument datings as well as the likeliness of a detected match visually, preventing the user from drawing false conclusions.

- **Semantic zoom**: We propose a customized semantic zoom approach that satisfies quantitative (distant reading) and qualitative (close reading) research interests alike.

We emphasize the utility of our visual matching system for musicologists by providing various usage scenarios. In a storytelling style, each scenario exemplifies how our system can be used for generating hypotheses on the auralization of an instrument or instrument type. Additionally, we report experiences gained during our project, which includes the iterative evaluation of our auralization system with musicologists, limitations due to the nature of humanities data and future prospects.

3.2.2 Related Work

Schlegel and Lüdtke [379] arrange instruments — Lutes and lute-like instruments — on a timeline to convey developments in instrument making. Annotated with descriptive metadata and related compositions for those instruments, the development of this instrument type can be explored visually. In opposite to the printed form, interactive timeline visualizations have been proven valuable for related research inquiries in digital humanities applications, typically directed towards person groups [7, 83, 220, 223, 306, 475]. Similar to time periods influencing a person's life, the development of instrument types is likely influenced. Much research has been done concerning time-oriented data visualization. Examples are given by Aigner et al. [4] and Brehmer et al. [48]. Both include different timeline visualizations, and the latter one proposes a taxonomy for timeline visualization in particular. These works highlight different visualization strategies for temporal data, like parallel lines or theme rivers [59, 164] and their ability to help in analyzing trends.

The time-dependent inspection of the instrument's careers visualization is as of now under-represented in literature. Typically, visualizations of instruments focus on structural aspects of instruments, often obtained through X-ray or computed-tomography [39, 175, 229]. Further, functional analysis of how an instrument generates sound is visualized [32, 43].

The static visualization by Schlegel et al. [379] is our motivation, but we propose an interactive visualization, making use of the timeline metaphor and digital interaction methods to help musicologists getting insight into the careers of instruments. A similar system is Continuum [7] that utilizes a semantic zoom functionality for a timeline but does not consider human career information. Another comparable approach is MusikerProfiling, which performs a similarity analysis for musicians based on their biographical data [199]. This work also addresses the visualization of uncertain temporal data, which has also been discussed in other works [217, 294]. Communicating such uncertainties is also subject to our work to prevent misinterpretations.

3.2.3 Design

In close collaboration with musicologists, we designed the system in an iterative and user-centered process to maximize the usability of our approach. Two musicologists specialized in organology and restoration were mainly involved in the development. This section reports on the project following the nested model by Munzner [313].

Domain Situation

Musicologists focusing on organology know much about the history and properties of inspected instruments. When instruments seemed outdated, they were restored, repaired or modified to get them ready for next performances. As it is mostly not easy to state which musical pieces were performed on a historical instrument, this work is motivated by musicologists who strive to picture an instrument's career with possible musical works (or genres) performed with it, creating an instrument's "aura". With traditional, analog means this task is near to impossible to be done. Due to various branches of musicology like composition analysis and organology, different methods and conventions of musical terminology exist. This makes it difficult to find exact matches among repositories listing musical instruments and compositions. We support generating hypotheses for the task of matching the instrument to musical pieces by digital means and a tailored matching algorithm considering instrumentation, time and location, to create hypothetically matches for further investigations. The two digital repositories on which our analysis is based on are explained in the next subsection. We further propose an interactive timeline visualization that helps to analyze the hypothesized matching pairs. All in all, we propose a system that supports musicologists investigating the research question *Which musical pieces have been performed on a particular instrument?* with an interactive tool outlined below.

Data & Task Abstraction

The data was harvested from different online sources and then transformed and cleaned to make them compatible with each other. Information on instruments are extracted from MIMO, a project for the standardized description and archiving of digital and multimedia information about around 65,000 music instruments in a database. The records include keywords and classifications, for the type of the instrument, as well as images and detailed events with different types. An instrument is defined with properties as described below:

$$I_i = \begin{cases} I_i^{titles}, \text{ set of instrument titles} \\ E(I_i), \text{ set of instrument events of } I_i \end{cases} \tag{3.1}$$

Where an event is described by its type, date and location (place name and coordinates). Information on musical works are listed in RISM, an international online documentation of more than 1,100,000 musical sources. Information like title and scoring were harvested for each source. Many musical works are annotated with related performance events, for which provided location and date are used for the matching task. Musical sources are described as:

$$P_j = \begin{cases} P_j^{title}, \text{ title of musical source} \\ E(P_j), \text{ set of performances of } P_j \end{cases} \tag{3.2}$$

After extracting and cleaning the data sets for the further processing, the resulting numbers were:

- 6,670 musical instruments $I_1, \ldots, I_n$ – with 6,826 events $E(I)$ and
- 24,760 musical pieces $P_1, \ldots, P_m$ – with 29,192 performance events $E(P)$.

Due to the geocoding during the cleaning process some place names could not be resolved and got lost and so some extracted events were discarded. Thus, the amount of completely described instruments and sources was minorly decreased.

Similarity between Instruments and Sources The matching between instruments and sources is determined on the basis of locations, dates, and instrument type of the corresponding events. Only events with all those information were taken into account. For musical sources, the instrumentation is given, and an instrument is labeled with terms for its type. For a matching task, one musical instrument or a group of musical instruments can be selected and matching scores for all possible pairs of instruments and musical pieces are determined dependent on three similarity scores. The similarity $S\big(e(I_i), e(P_j)\big)$ between an instrument event $e(I_i) \in E(I_i)$ and a musical performance event $e(P_j) \in E(P_j)$ is determined as

$$\begin{aligned} S\big(e(I_i), e(P_j)\big) = w_{inst} \cdot S_{inst}\big(e(I_i), e(P_j)\big) \\ + w_{time} \cdot S_{time}\big(e(I_i), e(P_j)\big) \\ + w_{geo} \cdot S_{geo}\big(e(I_i), e(P_j)\big) \end{aligned} \tag{3.3}$$

where w_k is the weight of the corresponding similarity measure S_k. The weights can be adjusted by the users during the matching process to modify search results. The combined similarity score is used to generate a result set of pairings. A limited number of t best matches for each instrument is taken into account for processing the visual output. Each similarity measure is described in the following.

Instrumentation Similarity S_{inst} Matching instrument and the musical piece is only possible if the instrument type is part of the composition. Therefore, we check if the labels of an instrument appear in the list of considered instruments for the musical piece. As the terminologies used in both repositories are not coherent, they needed to be mapped to each other. Each instrument is tagged with a set of titles, to describe what type of instrument it is. These could be special types of instruments, classes, and families of them. On the other side, the musical sources are equipped with information for what instrumentation the work is intended. The instrumental scoring of a RISM source is given by a list of abbreviations for each instrument playing parts of the musical piece, e.g. “vl, t-fag”. “vl” corresponds to “violin” and “t-fag” to “tenor bassoon”. Both title sets are available in different languages (e.g., English, German, French, Italian), which further complicated the matching task. An instrument is a possible candidate according to the titles, if one of its terms, or its translation, is included in the instrumentation of the source. S_{inst} is ranging from 0.0 to 1.0 depending on if it is an exact match, a substring match or none within the extended title set out of translations and overlying classes:

$$S_{inst} = \begin{cases} 1.0, \text{exact match}, \\ 0.5, \text{substring match}, \\ 0.0, \text{no match} \end{cases} \tag{3.4}$$

While an instrument with the title “violin” matches with score 1 due to the exact match, the instrument “bassoon” results in a score of 0.5 because of a substring match with the full RISM name “tenor bassoon”. This rather simple approach is used as the underlying repositories do not use uniform terminology. Instrumentation of a musical source from RISM is only given as a list of abbreviations. On the other hand, the available amount of information about the MIMO instruments ranges from names for the instrument, instrument families and partially concepts out of the Hornbostel Sachs classification [441], but these classification is missing in RISM. The collaborating musicologists pointed out that terms for historic instruments are inherently ambiguous and that there is not a comprehensive classification for instruments, especially not for such between different groups. Thus, a string matching based approach was best suited to determine instrumentation similarity.

Temporal Similarity S_{time} The temporal similarity score S_{time} between two events depends on the difference between the corresponding dates Δ_y in years and the maximally allowed temporal distance y_{max} and is defined as:

$$S_{time} = 1 - \frac{\Delta_y}{y_{max}} \tag{3.5}$$

This maximally allowed temporal distance with a default value of 25 years is user-configurable. By adjusting this value, the user is enabled to customize the matching process, depending on the research question at hand.

Due to the textual tradition of information, the granularity of temporal data ranges from exact dates to periods like years or centuries. Both sources comprise such temporal uncertainties. Annotations like “first half of 18th century” were translated into timestamps for the earliest and latest possible dates. In the case of a period for a given event, it is mapped to a single day (the mean day between the upper and lower border of the period) to be used for comparison. Furthermore, the temporal similarity is decreased by subtracting the period length in years $\Delta_{y_{span}}$ proportionally to the maximum temporal distance y_{max}. This is caused by the uncertainty of the exact event dating within the given period. So, the result strongly depends on the maximum temporal distance chosen by the user in combination with temporal uncertainties. In the case of temporal distances and in consideration of the mean day the maximum distance could be the worst case of $0.5 \cdot \Delta_{y_{span}}$.

$$S_{time} = 1 - \frac{\Delta_y}{y_{max}} - 0.5 \cdot \frac{\Delta_{y_{span}}}{y_{max}} \tag{3.6}$$

So, a given event in 1805 matches an event annotated with 1807 with a similarity around 0.866, with a maximal possible time difference of 15 years. Whereas an event in the period of 1800-1810 would match to 1807 with a value of around 0.533, even if the difference in years to the mean day is the same, due to its uncertainty. The temporal similarity is also defined between 0.0 and 1.0, so in cases of $S_{time}(e(I_i), e(P_j)) < 0$ we set $S_{time}(e(I_i), e(P_j)) = 0.0$.

Geographical Similarity S_{geo} The score for geographical similarity S_{geo} refers to the actual geographical distance between two places $p_1(x_1, y_1)$ and $p_2(x_2, y_2)$ that is computed with the great circle formula delivering the distance in kilometers [167]:

$$G = 6378 \cdot arccos\big(sin(y_1) \cdot sin(y_2) + \ldots \\ +cos(y_1) \cdot cos(y_2) \cdot cos(x_1 - x_2)\big) \tag{3.7}$$

With the user-configurable maximum permitted distance between the places of two events G_{max} (default value is 50 kilometers), S_{geo} is then defined as

$$S_{geo} = 1 - \frac{G}{G_{max}} \tag{3.8}$$

Task Abstraction

The outcomes of our algorithm are hypothetical matches between an instrument and a performance event. But the numerical results are hard to evaluate by the musicologists, they require interactive visual access in order to be able to regard a result in the musicological context to assess its reliability. To describe user requirements of the system, we utilized the task taxonomy by Munzner [314]:

- **Analyze:** At the beginning of our project, the musicologists outlined their needs and wishes for the system in their application field. Most of all they wanted to see and *discover* interesting new patterns or anomalies in the combination of the two data sets to generate and verify hypotheses for possible new research questions. In comparison to the numerical, algorithmic results, visualizations make it much easier to detect such groupings and patterns. Also, the communication of uncertainties benefits from visual encoding. With further qualitative investigation, they are able to *derive* new knowledge about the correlations of musical instruments and musical pieces. New and already known relationships have to be *present*able for the discussion between musicologists as well. Also, an *enjoy*able use of the visualization is focused, e.g. with a poster depicting all the modification states of a special musical instrument, enhanced through appropriate music, besides its presentation in a museum for visitors.
- **Search:** To interact with the underlying repositories, the users require to *search* the data sets in manifold ways. The musicologists need to *lookup* already known correlations for hypothesis verification. The search interface enables them to *locate* object identifiers and special instrument titles of interest. The visualizations and even the search interface encourages to *browse* and *explore* through the results and data sets by filtering for areas in temporal or geographical space.
- **Query:** Further tasks supported by the system are *query*, *identify*, *compare* and *summarize*.

3.2.4 Visual Encoding & Interaction Idiom

The presented visualization aim to display the results by focusing on temporal and geographical similarity and show them in separate, but linked views. To enable the user to inspect the results in an interactive way and to create hypotheses for further investigations, we created a comprehensive metaphor and visual encoding. To do so, we utilized a consistent color coding for the two entity classes, which are symbolized with two color schemes inspired by ColorBrewer [163]. Instrument events are colored in different discrete colors with a high red component, depending on the type of the event. Whereas musical piece performances are colored in green with different saturation from a continuous color scale, to visually encode the similarity score of the matching between the two entity classes. The overall legend can be seen in Figure 3.1. Also visible there is the choice of different shapes to symbolize instrument events as ellipses and matching piece performances as rectangles.

Figure 3.1: Overall color coding, with two color schemes for the different entity classes. The color scale over the saturation of green encodes similarity of one piece performance to a instrument event.

Timeline

We use a timeline to visualize the resulting matches in dependence of the temporal dimension (S_{time}). To minimize the visual clutter, we group the result set entries by single instruments. So every matched instrument $I_i \in I_1 \dots I_n$ is symbolized by one row on the y-axis, started by an eventual image of the instrument to offer the first view of it. If no image could be found for the instrument, the place at the beginning of the row stays blank. The x-axis represents the time, so the temporal located instrument's career events $e_1 \dots e_o \in E(I_i)$ are placed along with the row's horizontal extension. These events are enhanced by the matched musical pieces $P(e)$ with $e \in E(I_i)$ to show their relation.

Uncertainties In the case of uncertainty, the inaccuracy is communicated by an out fading border and width of the event's glyph, as visible in Figure 3.2. The height of each row (I_i) is given by the maximum amount of matches from $P(E(I_i))$ in it.

One upcoming challenge was the fact, that large objects draw more attention than smaller ones. Due to the uncertainties and the focused similarity measures, lower (more unlikely) matches are getting more screen space on a timeline or map than exact matches in temporal and geographical consideration, because of their higher distances. Equally in calculating and visualizing the result sets, closeness is the significant property to describe likeness. To encounter that, we implemented the continuous color scale and with it, in combination with transparency, the lower matches are fading out towards the borders of the maximally allowed distances.

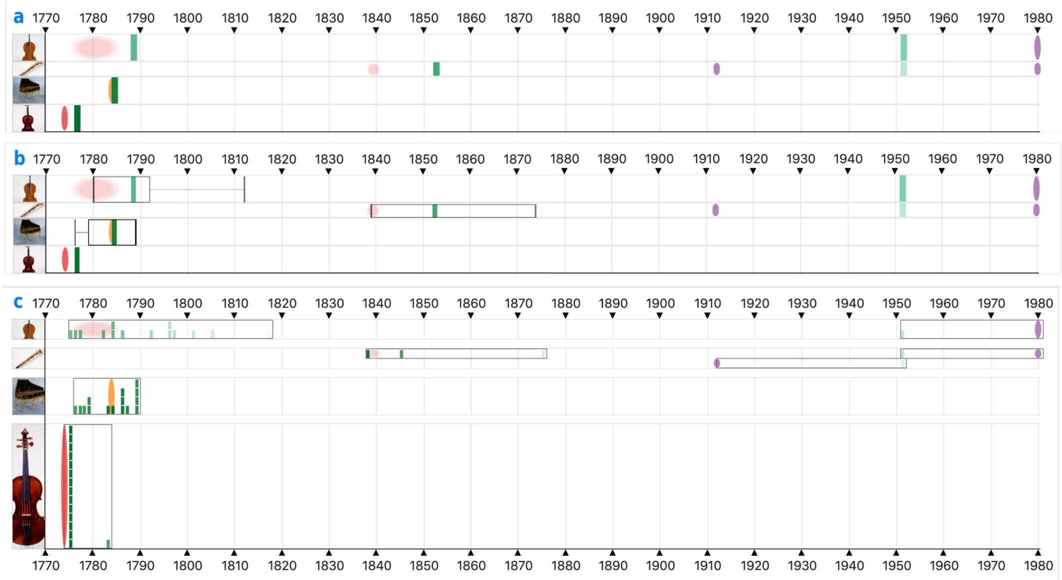

Figure 3.2: The different semantic zoom levels enable distant reading of distributions of matched results (**a**,**b**), as well as the close reading of all results in detail. In the highest zoom level (**c**) the musical piece performances are stacked on each other, creating a bar chart and encode the quantities and qualities for each instrument event.

Semantic Zoom Following the Visual Information-Seeking Mantra from Shneiderman [398], the user can browse through different semantic zoom levels.

The first zoom level of the timeline shows a first overview of the matched instruments and their events. All possible similar pieces $P(e)$ of each instrument event $e_1 \ldots e_o \in E(I_i)$ are summarized in one glyph at this level. This glyph is a rectangle with a width of one year on the timeline, positioned on the average year of all summarized performance events. The color is given by the sum of scores for the temporal similarity of all binned matches. With this view, it is possible to get a first overview of the temporal distribution of the matched events in a distant reading manner. Like on a classical heatmap, whole areas of interest or special outliers could be derived and picked for further investigation. The overview of some matched instruments is visible in Figure 3.2**a**.

The second zoom level extends the rectangle glyphs to box plots, to uncover the distribution of the matched performances. The previously drawn rectangles remain as medians and get surrounded by their quartiles. Additionally, whiskers indicate the minimum and maximum extension of the quartiles over time, but outliers were ignored. An example of box plots could be seen in Figure 3.2**b**.

On the last zoom level, the box plots become bar charts to reveal all underlying performance matches. Each matched musical piece is symbolized by its small rectangle at the year of its performance. We stack multiple performances in the same year on top of each other so that they are creating a bar chart like glyph for the distribution of all matches for one instrument event $e \in E(I_i)$. To clarify the connections of the bars, all matched $P(e)$ are framed by a thin border from earliest to latest performance. This time frame could be expanded via one checkbox to show the minimum and maximum possible year (y_{max}), to show if there would be more room for further sources. Periods around the instrument's events are stacked on top of each other too and margins between the rows are growing, to maintain the separation of the instrument rows as visible in Figure 3.2**c**.

Shape of Similarity Although the shapes of piece performances are changing over zoom levels, an overall shape of all matches to an instrument is recognizable. Width, height, and saturation are indicating inaccuracy, destination, amount and quality of the underlying matches. A thin, high and saturated shape of e.g. a bar chart shows much more certainty and quantity than a broad and flat shaped frame around the bars. These are patterns to search for during the analysis, as well as the visual encoding for uncertainty.

Interactions To explore the result set of matches a variety of interactions were applied to the visual elements. First of all the interactive search form with its text fields, buttons and easy to use filter bar "VisualSearch"[4] enables visual analytics and is visible in Figure 3.4. Additionally to the dynamic adaption to different research questions and changing search results via search form, the user could change the sorting algorithm of the instrument rows in the timeline. The default is the chronological sorting, where the instruments are sorted by the dates of their matches. Other sorting methods are the average or the sum of all matches of one instrument, to get a ranking by quality and quantity of resulting instrument/piece pairs. With them, it is possible to encounter the demands of different research questions, like the penalty of the set of matches through low similarity scores via the average.

For a closer look at one single instrument and its matches, it is possible to click on the instrument images or their event glyphs, to filter the whole result set. There, due the small number of elements, the elements are able to become larger. Some information about the matched events are accessible via mouse hover over their drawn glyphs, like seen in Figure 3.3. Both, timeline and map, are connected through the hover effects, to bring geographical and temporal dimension into context.

[4] https://documentcloud.github.io/visualsearch/

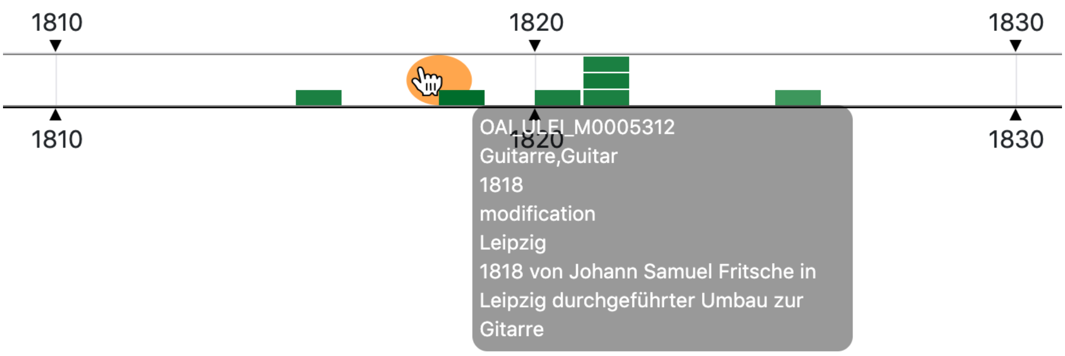

Figure 3.3: The tooltip uncovers, that this lute was converted into a guitar by Johann Samuel Fritsche in 1818 in Leipzig, Germany.

Figure 3.4: The timeline of a trombone from the Music Instrument Museum of Leipzig University in its different zoom level states.

Map Analogous to the timeline, the map is focusing on the geographical similarity of the different events. Also the most visual metaphors are the same. Shape, size, and color are indicating entity class, amount of summarized entries and type, respectively the geographical similarity score. Because of the different dimensions, and thus overlapping of events, it is not possible to group the result set after instruments in the same way as at the timeline, but overlapping data points get clustered. The clusters are divided into separate glyphs for summarized instruments and piece performance events in that cluster, as seen in Figure 3.6. If multiple types of instrument events are clustered together, they are symbolized by a pie chart in the mentioned color map. When zooming into the map, clusters of less than eight items of one entity class are split into single features, placed around the first feature in the center on a circular path. It is possible to show a circle around the single instrument events to display the maximum allowed distance between the matched items, analogous to the time frames around the timeline's bar charts. To highlight the connections between the entities, lines could be drawn, which connect instrument events with their matched piece performance events, as visible in Figure 3.5. We waive to draw the detailed connections between split single elements, because of the visual cluttering.

3.2.5 Use Cases

In discussion with four musicologists, we observed multiple use cases during their use of the system, which underline the work with the visualizations and the system and point out possible improvements as well.

The Protestant Trombone

The first is the case that an object is exhibited in a display case e.g. in a museum. With the knowledge about all of its conversions and stations, its life could be enriched by possible musical piece performances. For a trombone of the Music Instrument Museum of Leipzig University (Germany)[5], they chose to set $G_{max} = 200\,km$ and $y_{max} = 50\,years$. Inspecting the timeline from Figure 3.4**a**, the musicologists saw two distinct red production events of it, in each case with a given period of 10 years, indicated by the stretched and out fading ellipses. When hovering over

[5] https://mfm.uni-leipzig.de

the events, they noticed that the production of the whole instrument is divided into the manufacturing of the lower part around 1740 and the upper part around 1785. When zooming in (**b** of Figure 3.4), the glyphs get enhanced by the box plots around them, uncovering the distribution of matched performances. A first glance shows, that the left box plot has a longer range of whiskers than the other one. On the next zoom level (**c** of Figure 3.4) the single matched performances become visible. To assess the quality of the recommendations the musicologists wanted to get insights into the first matched performances for each instrument event. Without question, the first half of the trombone is not playable without its other half. Nevertheless, a closer inspection of the first musical pieces by hovering revealed, that some of them are different parts of an opera. Also striking is, that many of the matched musical pieces are sacred songs. That leads the users to the geographical similarity of the result set. Both parts of the trombone were manufactured in Nuremberg (Germany) and the musical pieces were performed in cities around that place in the radius of G_{max}, as displayed in Figure 3.5. With the additional knowledge of the musicologists, it turns out, that all cities have been Protestant, except for Munich, which was Catholic. So considering the high amount of Protestant pieces, from Protestant composers, in the result set, e.g. Frankfurt am Main is culturally closer to the instrument from Nuremberg, than Munich, although Munich is geographically nearer. Despite everything, for users it is at least possible to get an insight into the music e.g. operatic arias composed for trombones in Southern Germany around the late 18th century.

The Playlist for a Violin

Another possible use case is the generation of a "playlist" around a special instrument or a group of it. For example an imagined chamber orchestra with multiple concertmasters, who play Italian violins. With the system now it is possible to easily generate a playlist of matching musical pieces for a themed concert or the production of recordings around ancient violins. The musicologists started with the first look on all of the available violins in the data set and their best matches. Selected settings here were $y_{max} = 25\ years$ and $G_{max} = 50\ km$. Noticeable at first glance was the clear gap between matches around 1850 and 1870. Looking at the map showed, that most of the instruments were located in Germany and just circa 10 percent of them in Italy. Focusing on the seven violins from Italy with matches within a distance of 30 years and 75 kilometers, the timeline is changing to Figure 3.6. With such a condensed set of instruments and nevertheless a manifold variation of possible musical pieces, the musicologists suggested "A foray through the Italian baroque for the violin" as one name for the playlist, where stations could be Rome around 1710, Cremona around 1750 and Parma around 1810. Matching pieces are from composers like Antonio Vivaldi or Andrea Bernasconi and primary operatic arias. Interesting to see is the already mentioned gap after 1820 in Italy and the raising violins and performances on the north side of the Alps. Also noticeable by further investigations, is that Italian music was not just played in Italy. For example the source "Didone abbandonata"[6] made its way from Milan (1738) over Venice (1741) to Munich (1756).

[6] https://opac.rism.info/metaopac/search?View=\rism&id=450014602&View=rism

The Conversion of Lutes

The lute instruments are an ancient plucked string instrument family. Due to their high value the lutes, some particular instruments experienced multiple developments and changes over the time from classical lutes over mandolins and theorbos to guitars, picturing the passed trends. The

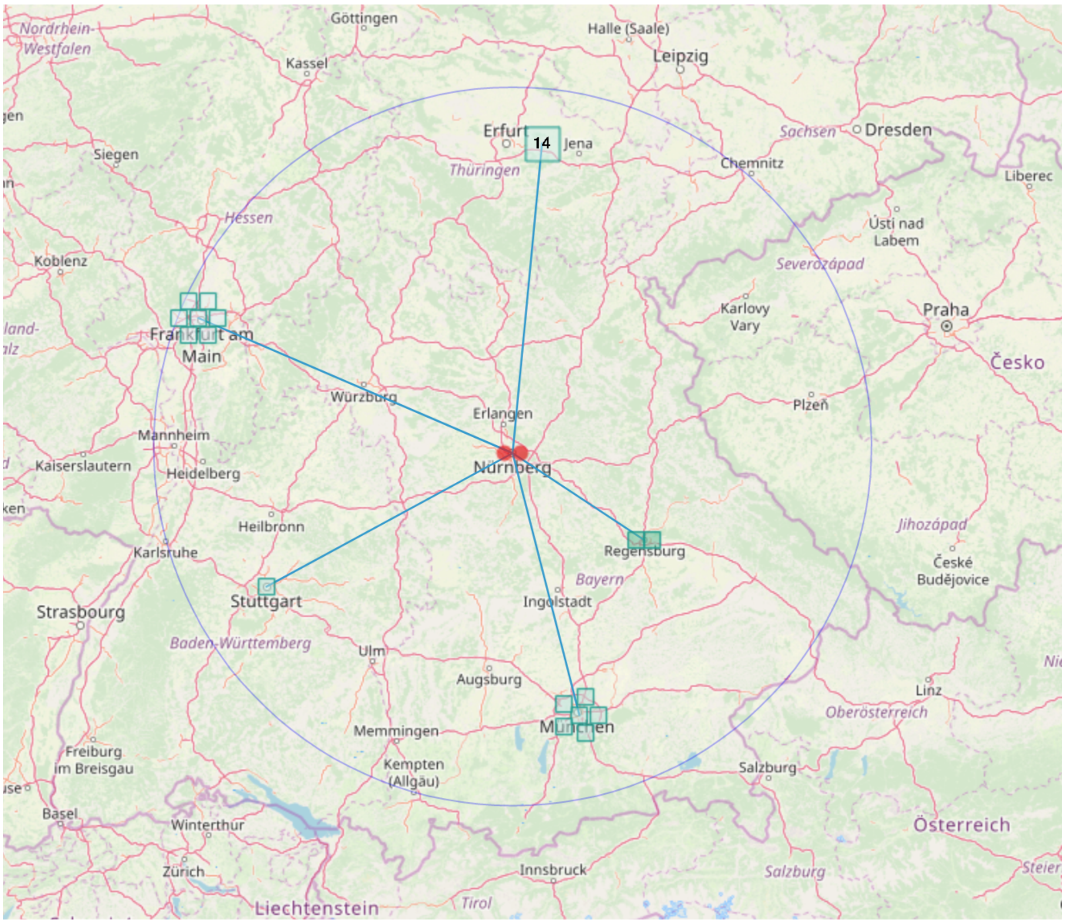

Figure 3.5: The map for a trombone from the Music Instrument Museum of Leipzig University, produced in Nuremberg (Germany), surrounded by its matched piece performances.

Figure 3.6: All Italian violins with their piece performance matches within a distance of 30 years and 75 kilometers.

search for such instrument families in the presented system creates the timeline and map view from Figure 3.7.

Apparently, the timeline is divided into three different characteristic epochs. The first episode is for the renaissance and baroque european lutes like the one in the row **d** in Figure 3.7. Unfortunately, musical pieces for lutes from RISM are very rare (a search on RISM for lute as instrumentation gives 38 results). After that period, the music culture was changing and with it, performance practices. The lute was displaced from the established ensembles because it had no place in the rising orchestras.

The many exact datings of instrument productions in the second epoch (1770 - 1860) may come from the high amount of good logged contract manufacturing for the courtly culture, the analyzing musicologists assumed. Most of the instruments in that period are mandolins and first guitars. The data of the lute-guitar in row **c** of Figure 3.7 is manually enhanced and corrected by a musicologist specialized on lutes. In MIMO the instrument is tagged as lute-guitar with two production events. The information, that the instrument was manufactured as a classical lute (first half of the 17th century) is only available in the textual metadata of the events. As well as the conversion of the instrument into a lute-guitar in 1818 is written down, but not easily automatically processible, as seen in Figure 3.3. Such example shows the real value of the system to visualize and auralize a particular instrument career, cause of the musical changes of matched piece performances to its station.

The last episode is dominated by uncertain production dates of guitars. Due to that the amount and quality of matches are decreased. The musicologists working with the system assumed the more industrial production of instruments. These instruments were produced on stock and not for a specific customer who made an order. This might be the reason for the uncertain manufacturing records. Besides, the lutes experienced a revival through the conversion to lute-guitars or bass lutes, like the one in row **b** of Figure 3.7, which were used in operas e.g. the hypothetically matched “Meistersinger von Nürnberg” [7] by Richard Wagner.

The Historical Performance Practice

Even the other way, finding matches to one selected musical piece, is conceivable. Imagined a given music manuscript, with its past performance dates and maybe additional knowledge about the work e.g. the composition event. With such information, feasible historic instruments come into consideration by the use of the system, to perform the musical piece in a way of historically informed performance practices, with appropriate instruments.

3.2.6 Results

Discussion

While evaluating the system through the work with musicologists, we observed the following effects. Different close and distant reading research questions are supported by the system. For resilient results, further close reading is still necessary, but the system is capable of revealing so far unseen correlations, now possible with a digital humanities approach to musicological data. The different levels of the semantic zoom create a smooth transition between temporal granularities.

[7] `https://opac.rism.info/metaopac/search?View=\rism&id=270000986&View=rism`

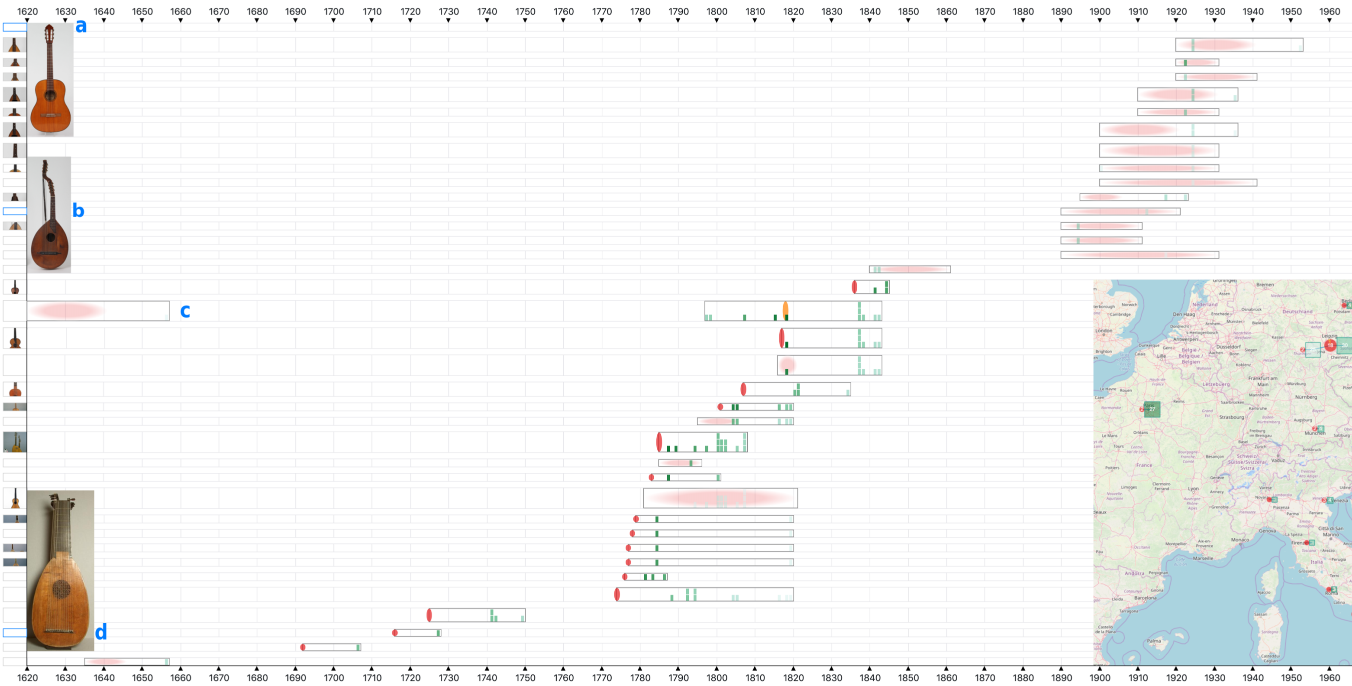

Figure 3.7: All lutes and its similar instrument families with their piece performance matches within a distance of 50 years and 100 kilometers. Visual striking and interesting are the three distinct episodes and the differences between the certainties inside of them.

Even if the matching results are not exact matches in the real world, at least we receive indications about how the music was intended to sound at the dedicated lifetime events of one instrument or their instrument family.

One advantage could be the research and education in organology, instrument careers and socio-cultural developments over the centuries of music. Indirectly the system creates a similarity measure for instruments through the analysis of similar events and shared possible performances. The use cases show that available databases and the post-processing of data sets have yet to be improved in order to increase the quality of results of the recommendation system. For example, detailed information about tuning and tones are missing for a better instrumentation similarity analysis. But for now, the system satisfies the intention of creating hypotheses of joint appearance, which can be verified or falsified by further inspections of musicologists.

Limitations

In general the amount of displayable items is not limited. All instruments in the timeline are stacked atop each other so the scrollable height is growing with each new entry. However, the number of instrument rows and related events is limited by the amount that is humanly processible. We observed a result set with 150 oboes from one museum with the same production event date and location and the same matched musical pieces were stacked on each other, using a lot of screen space. This output requires the screen's height three times (depending on resolution and used minimum of instrument rows height) but is also negligible by the user who is aware of the general quality of the data. Also, the system is not meant to review, but rather to direct towards new hypotheses. Such review, especially verification of suggested facts, has to be performed intellectual with additional knowledge. Nevertheless, the falsification is easily possible by using the visualizations, but this use case underlines again the dependence of calculated and displayed statements on the quality and quantity of the used data points.

Future Work

The measurement of similarity will be improved e.g. by the consideration of geopolitical information like provinces and countries. Therefore, the aggregation of information from other repositories and a better alignment of the different existing vocabularies is necessary. Also, the derivation of new information out of existing is possible. For example, the database of the musiXplora [223] contains over 32.000 persons in the musical context with a variety of information about them, e.g., the denomination of musicians. Hypotheses like the denomination of cities (as mentioned in the first use case in Section 3.2.5) could be derived from the denominations of all locally born persons. Further, the system is expandable by e.g. a force-directed graph for the results of the recommendation system. Therefore instruments or musical pieces could be grouped depending on the demand of research questions. A box plot glyph could be evolved to a bean plot [213] for the better creation of shapes for the matched results. Furthermore, we want to increase the linkage of the different attributes and views e.g. by implementing a time slider for the map, to see the geospatial trends of the two entity classes over time.

3.2.7 Conclusion

Due to the increasing amount of digital cultural heritage resources, user interfaces that support aggregation, mapping and linkage gain more and more importance. Our project aimed to find relations between musical instruments and historical performances of musical pieces. To encounter this, we cooperated with musicologists, aggregated and linked two digital repositories. In addition, we defined a multi-faceted similarity measure for the likeness of two matching events. To achieve the ability of qualitative close reading and quantitative distant reading of the results, we designed a new timeline metaphor with semantic zoom levels accompanied with a map to review results in a temporal as well as a geographical context. The presented use cases indicate the value of our approach to support new research questions in musicology.

3.3 Paper 3: Visualizing the Aura of Musical Instruments

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3.3.1 Introduction

Many historical musical instruments are resting in depots or are presented in showcases in music museums. Digitization is one of the current key strategies to gather data and to make those instruments virtually accessible through online repositories. But not all of them are linked together, and so relations between related objects remain hidden. Cooperating with musicologists, we unfold the history of musical instruments by "auralizing" [409] them through matching compositions. The motivating research question is, in which particular performances of compositions a musical instrument was used. Therefore we assign musical pieces from RISM [360] a digital collection of musical compositions, to musical instruments from MIMO [317], a digital repository of meta- and media-data on musical instruments in public collections. A multi-facetted similarity measure generates matching results between the two repositories automatically and interactive visualizations. We propose an extension of this process by a tag cloud picturing the aura of instruments of interest. The system is evaluated by musicologists who investigated different scenarios using the tool.

3.3.2 Previous System

In our previous work "A Timeline Metaphor for Analyzing the Relationships between Musical Instruments and Musical Piece", we proposed a system for the calculation and visualization of hypothetical relations between musical instruments from MIMO and musical pieces from RISM [252]. We take geospatial, temporal and descriptive meta-information into account to assign musical instruments to musical pieces. These attributes are used to define similarity measures which describe the likeness of a musical instrument playing a part in a particular piece performance. The result of the matching process is a list of musical instruments and the assigned musical piece performances. Schlegel et al. created a static visual timeline for types of lutes and lute-like instruments, enhanced with appropriate compositions [379]. To visualize such pairings interactively, we designed a new timeline metaphor, where every instrument has its dedicated row. Distant and close reading research questions can be answered through different semantic zoom levels, what has previously been demonstrated for compositions [7]. As described by Khulusi et al., data on musicology include uncertainty aspects [217], which are visually encoded in our approach. The timeline enables the explorative analysis of hypothesized matches and a map as an additional view helps the user to validate or falsify the automatically generated suggestions. So the instruments' careers are visualized through their temporal and geographical located events in timeline and map. Now we propose an additional view to picture the aura of one or a group of musical instruments of interest.

3.3.3 The Aura

The timeline and map generate visual patterns, and potentially interesting findings stick out. The previous version of the system only allowed to select an individual musical instrument after filtering the results via search terms and clicking a particular instrument, getting to a single close reading view. The aura of an individual or multiple instruments was just perceivable by a follow-on, laborious clicking on each matched piece performance. The extended system now enables to select instruments via a rectangular selection box by click-and-drag in the timeline or map. This selection filters the result set and leads to the refreshed multi-view screen of timeline and map, including a new visualization depicting the aura of instruments.

Tag cloud for the Aura

The aura of instruments is pictured in the form of a tag cloud. It shows the resulting instruments, described by words aggregated from the matched musical pieces. The arrangement of words is automatically determined by a force directed graph drawing algorithm [238], in which each item is a node and the links between them represent joint appearances in the same category. This leads to forming clusters, inspired by TagPies [196]. In the cloud's center, each instrument is symbolized by its image, or a placeholder image in a circle. The words, whose sizes are determined according to the number of occurrences, are taken from four different attributes of musical works, and, additionally, the titles of the instruments. So the words appear in five different colors to quickly depict the instrument's aura visually. In most cases, the largest cluster (in purple) is built by the tokenized titles of the musical pieces found in the matching process. Due to the variety of possible languages, we did not apply further language processing like stemming or lemmatization. Nevertheless, the token sets are cleaned through stopword lists of the most frequently used languages like German, English, and Italian.

Furthermore, the names of the musical piece composers constitute the second cluster (in green) of the tag cloud. Due to the length of full names, they were cropped and only the surname is displayed. Thanks to the additional meta-information about the composers, the user can inspect the details by hovering the name tags and see the composer's full name and lifetime. Additionally, genre names (in red) and languages (in blue) of the manuscripts are displayed in separate word clusters of the tag cloud.

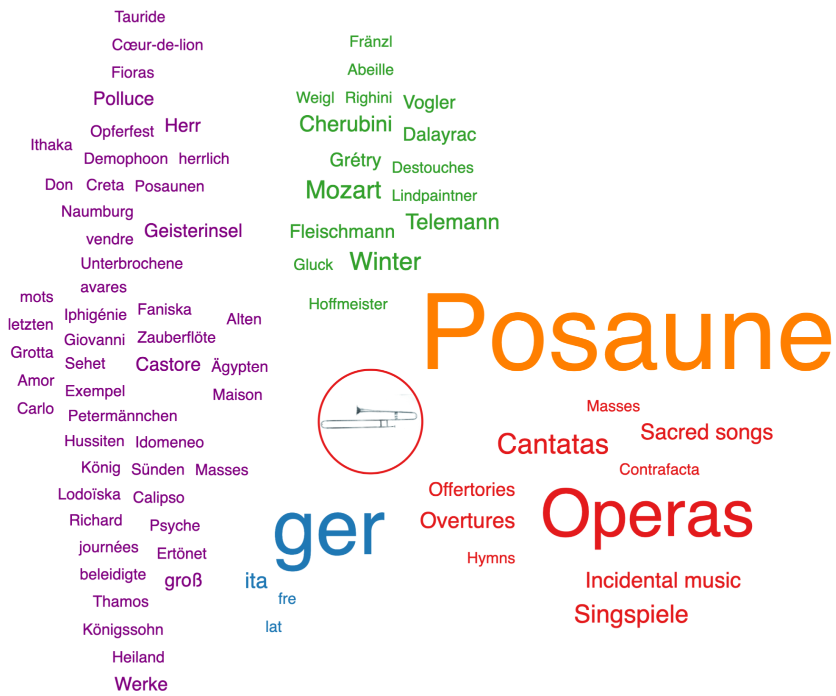

Figure 3.8: The generated tag cloud for a trombone from Leipzig, Germany and its matched compositions within a range of 50 years and 200 kilometers.

3.3.4 Use Cases

The Protestant Trombone

The visual exploration of a trombone [465] originating Nuremberg, Germany has been described in our previous paper [252]. The inspection of matched pieces on the map reveals that they were performed in some cities close to Nuremberg. The tag cloud highlights that the most frequently matching genre is the opera (closely related to "Singspiele"), and German ("ger") as the major language. In Figure 3.8 frequent terms in the titles are "Zauberflöte" and "Giovanni", in which trombones were used, as well as "Mozart" as the corresponding composer. A closer look reveals many terms related to religion. German cantatas, sacred songs and numerous names including words like "Herr" (lord), "herrlich" (wonderful), but also "Sünden" (sins) and "Opferfest" (sacrifice) from Peter von Winter and Georg Philipp Telemann are found in the resulting list of musical piece tags prominent in the word cloud. The musicologist working with this use case commented that the denomination was very important around 1800. Additionally, he took the predominant denomination of the piece performances' locations into account. All cities were predominantly Protestant, except the Catholic Munich. Thus, the trombone from Nuremberg may be better auralized through Protestant songs from one of the culturally closer cities like Frankfurt am Main, even though it is geographically farther away than Munich. Clicking "Cantatas" shows a list of all cantatas in the musical piece matches, for example "Ertönet bald herrlich ihr letzten Posaunen" [416] (also tagged as a sacred song) having even "Posaune" (trombone) in its title. The song was performed in Frankfurt am Main and was composed by Georg Philipp Telemann who is tagged as evangelic in the musiXplora [221].

Lutes and Lute-like Instruments

The history of plucked instruments like lutes and lute-likes is pictured by a second use case. Three dedicated epochs are visible in the timeline in Figure 3.9, and the corresponding tag cloud is viewable in Figure 3.10a. The first epoch (1620–1760) refers to the classical lute, indicating a very sparse occupancy due to the low amount of pieces dedicated for lutes in RISM. However, a wide distribution of genres is depicted in the word cloud in Figure 3.10b. The second epoch (1770–1810) is characterized by numerous precise datings (see Figure 3.9) for the production of the instruments. This might be contractual works commissioned by the courtly society because lutes were highly appreciated instruments at that time. Also, the word cloud gets more dense and manifold (Figure 3.10c), especially, the amount of mandolins increases. The third epoch (1870–1960) is marked by very uncertain production dates because of their more industrial production, visually encoded by more transparent and wider red ovals in the timeline. Also, this episode was the time where lutes and lute-like instruments only survived by being transformed into bass- lutes or guitars to play roles in operas because they were not part of uprising orchestras, as seen in Figure 3.10d.

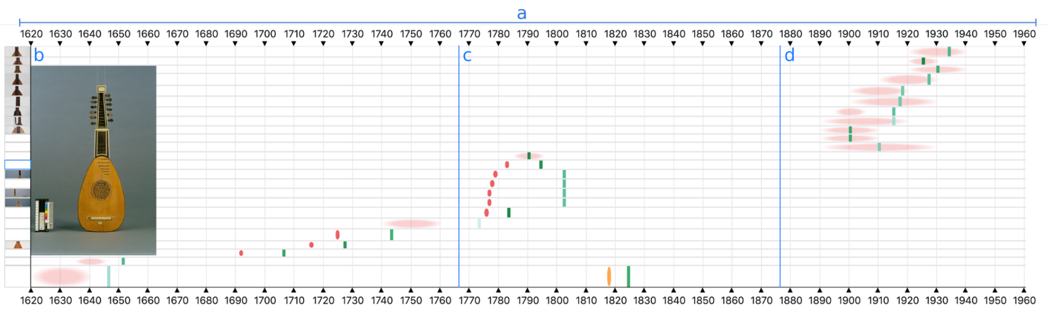

Figure 3.9: All found lutes and lute-like instruments with their matching piece performances within a distance of 50 years and 100 kilometers around the instrument events. For details, see the original publication [252].

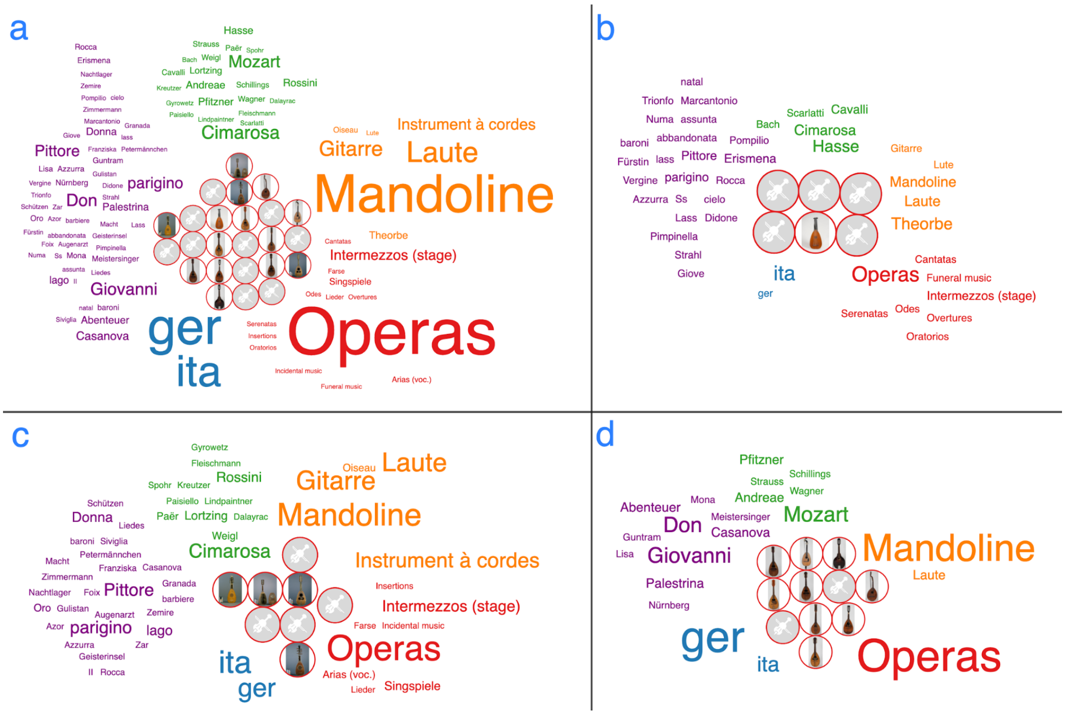

Figure 3.10: Four different tag clouds for lutes and lute-like instruments summarizing all pairings of instruments and compositions for the time ranges (a) 1620–1960, (b) 1620–1760, (c) 1760–1870, and (d) 1870–1960.

3.3.5 Conclusion

While historical musical instruments are resting in showcases or depots of museums, digitization efforts serve us with intangible data about them. This data could be used to make the musical instruments and their history perceptible. We extended our visualization system by an interactive tag cloud to picture the career and aura of an instrument or group of instruments of interest in a manifold way. The created aura is composed of word clusters for five different attributes of the matched composition or instrument giving an overview of the selected data subset. This visual depiction could be presented to visitors of museums next to showcases to contextualize instruments through their music and to bring their particular careers to life.

4 Sustainability of Materials used for Musical Instruments

"When you get far enough away from all the organisms and the little bits of things you see the environment in another scale of magnification. But actually, the whole thing is arranged in a polar system where the enormous depends on the tiny and the tiny depends on the enormous, and you get a relationship between these extremes which can be called a transaction."
– Alan Watts, The Myopic View of the World [446]

4.1 Overview & Contributions

In the intricate tapestry of our world, natural heritage as part of intangible cultural heritage are threads interwoven in the fabric of human existence, embodying the delicate balance between nature, culture and society. In the center of this balance is the art of musical instrument making, an enduring legacy that marries the physical gifts of the natural world with the creative expressions of humanity.

Musical instruments, especially those of high value and exceptional quality, are crafted from natural materials, making them not only artifacts of cultural heritage but also dependents on the ecological harmony of specific ecosystems. These ecosystems, often threatened, serve as the cradle for the raw materials that give life to musical harmony.

As we delve into the realms of natural heritage and musical craftsmanship, we uncover a complex narrative of interdependence and vulnerability. The craft of making musical instruments, a cherished intangible heritage, faces threats from efforts to preserve biodiversity.

This chapter ventures into the exploration of these complex matters, adopting various lenses of magnification to examine the interlinked and interdependent systems at play. We engage in a semantic zoom, peering into the entities and their hierarchies, from musical instruments organized into instrument groups of a western symphony orchestra and composed of specific parts, to the natural materials that form their essence. The journey traverses multiple levels of magnification, revealing the intricate biological taxonomies of the species used in instrument making, organized in genera, families and kingdoms, and the geospatial divisions that contextualize these materials' origins defined by countries, ecoregions, and artificial hexagonal grids.

The assessment of economically and ecological threats to these intertwined systems unveils a web of complex effects, highlighting the challenges of communicating such intricacies to a broader audience. Domain experts themselves benefit from interactive visualizations that contextualize these dynamics, although the diverse scales of threat assessments and the differing priorities of biology and geography (prefer specific details) versus visualization (prefers generalization) present unique challenges.

The collaborative and trans-disciplinary research on these complex matters is documented by two consecutive papers building on top of each other.

Whereby the Paper 4: **Visual Analysis of Diversity and Threat Status of Natural Materials for Musical Instruments** [254] introduces the background and used manifold data as well as the visual design which was conducted in an iterative participatory design process, involving a variety of practical and scientific domain experts. The result is *MusEcology* a multi-view visual analytics tool specifically crafted for the needs of the involved domain experts and policy makers.

But because the discussed complex challenges and their possible solutions call for a comprehensive understanding by broader public and then for actions, we attempted to lower the hurdles, break down the complex topics and introduce them step for step by telling a story via Paper 5: **Visualization-based Scrollytelling of Coupled Threats for Biodiversity, Species and Music Cultures** [253].

Instrument making or instrument playing, as a manifestation of cultural heritage, embodies traditions steeped in history and expertise. Yet, even experts may lack a full understanding of the complex requirements spanning across different domains. Our explorations are not aimed at limiting cultural practices like instrument making or performances but at fostering sustainability to preserve these traditions for future generations.

However, challenges arise as practical domain experts or the interested public may find nested and interactive visualizations overwhelming. Storytelling, particularly through scrollytelling where scrolling propels the narrative forward, offers a gateway to simplifying these complexities. This storytelling leverages the comprehensive system of *MusEcology*, reusing its data, transformation workflows, and visualizations, augmented with multimedia annotations. It not only demystifies the intricate connections between natural heritage and musical instruments for the public but also outlines pathways towards sustainability.

Focusing on the string instrument bow, with its unique characteristics and requirements, serves as a poignant entry point and use case to these discussions. It exemplifies the broader issue of sustainability in the face of cultural and ecological challenges. Through this lens, we aim to enlighten a wider audience about the nuanced interplay between natural heritage, cultural practices, and the imperative of sustainability, shedding light on the profound connections that many may not realize impact their daily lives.

The main contributions of both works regarding *MusEcology* include:

1. **Integration of Multidisciplinary Knowledge:** *MusEcology* combines expertise from various fields such as instrument making, material science, geography, biology, ecology, and computer science, showcasing an interdisciplinary approach to understanding the global impact of musical instrument production.
2. **Comprehensive Database:** The project compiles an extensive database linking musical instruments to the natural materials they are made from, including data on species' ecological threat levels, trade regulations, and geographical distributions. This database includes 5,965 assignments across six musical instrument groups, linking them to 758 species, emphasizing the wide variety of natural materials utilized in instrument making.
3. **Innovative Visual Metaphors and Design Features:** The platform introduces several visual metaphors and design features, such as:
    - **Visual Metaphors:** Using glyphs to symbolize the ecological and trade-related threat status of species.
    - **Linked Views Design:** Tailored for complex datasets, facilitating exploration of the interconnections between musical instruments, materials, and their ecological contexts.
    - **Multi-Layered Geospatial Design:** Allows investigation of species distribution with respect to political and ecological boundaries.
    - **Species Timeline:** Illustrates the evolution of ecological threats and trade regulations affecting species.
    - **Target-User Driven Design:** Ensures accessibility for users with non-technical backgrounds.
4. **Interactive Platform with Coordinated Views:** *MusEcology* is an interactive platform that provides multiple coordinated views (Orchestra View, Material View, Threat Assessment Timeline, Diversity Map), enabling users to explore the data from different perspectives and understand the intricate relationships between music, material use, and conservation.
5. **Use Cases and Expert Feedback:** *MusEcology* is additionally described by use cases demonstrating the platform's utility in offering insights into the sustainability of musical instruments and their ecological impacts. Feedback from domain experts underlines the platform's potential in fostering interdisciplinary understanding and informing sustainable decision-making processes.
6. **Scrollytelling as an Effective Communication Tool:** The addition of storytelling functionalities lowers the hurdles by interlinking stories with the interactive visualizations, so that they are explaining themselves through an iterative build up and explanations. By scrolling through the right part of the screen the users intuitively understand complex threats

to biodiversity, species, and culture illuminated by multimedia annotations including images, videos, or sound recordings to increase the immersion in addition to visualizations. Whereas the left part of split screen scrollytelling design consists of an animated map, taking the user on a journey flying through different geographical and semantic zoom levels, using various polygons, glyphs and map layers such as satellite images.

7. **Informal Evaluation with Diverse Participants:** An informal evaluation with participants of different backgrounds indicated that the scrollytelling approach is relatively intuitive and significantly contributes to learning about the complex interconnections between biodiversity and instrument making. Participants reported gaining new insights and highlighted the value of integrating rich media, such as sound and video, to enhance the storytelling experience.

8. **Discussion on Limitations and Future Extensions:** The works acknowledge the limitations due to data availability and accuracy, and suggests future directions for enhancing the platform, including expanding the database to cover more musical traditions, incorporating alternative materials, and extending analyses to address the impacts of climate change on musical instrument materials. Furthermore the articles acknowledge challenges such as the ambiguity of common trade names and the need for comprehensive scientific findings for some musical instruments and their source species. It also outlines future work, including exploring deeper zoom levels on specific protected areas and adopting additional narration techniques to enhance user engagement and understanding.

Overall, *MusEcology* represents a significant step towards integrating ecological considerations into the cultural domain of music, offering a novel tool for researchers, instrument makers, musicians, and environmentalists to explore the sustainable use of natural materials in musical instrument production. The potential of VBS demonstrates to bridge the gap between scientific data and public understanding, particularly in the context of conserving biodiversity and cultural heritage. Through the lens of the symphony orchestra's instruments, it showcases how storytelling can raise awareness and foster a deeper appreciation for the intricate relationships between culture and nature.

4.2 Paper 4: Visual Analysis of Diversity and Threat Status of Natural Materials for Musical Instruments

Jakob Kusnick[1], Silke Lichtenberg[2,3], Daniel Wiegreffe[4], Elisabeth Huber-Sannwald[5], Udo Nehren[3] and Stefan Jänicke[1]

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[2] University of Passau, Passau, Germany
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Abstract: *A classical symphony orchestra consists of up to 29 musical instruments manufactured from up to 758 distinct natural materials. The interrelationships between the extraction of raw materials for instrument making, the international trade conditions, and the protection status of endangered species and their ecosystems are highly complex and have yet to be sufficiently scientifically examined. However, rapidly progressing climate and ecological change call for sustainable solutions. To address this challenging task, we present MusEcology, a new interactive decision support system based on visualizations. The interactive visualizations offer entry points for users of various backgrounds to explore the interrelationships between music and natural resources. The underlying objective of the tool is to ensure that the (1) data processing correlates related data resources, and (2) visual interfaces and interaction schemes stimulate new interdisciplinary research on complex systems interactions, and finally, (3) support high-level decision-making to find alternative pathways towards sustainable instrument making.*

4.2.1 Introduction

Some of the most famous pieces of classical music are composed for symphony orchestras [310]. A symphony orchestra achieves the desired sound only when each musician contributes with their musical instrument in a coordinated and harmonic way. The quality of those musical instruments depends, in turn, on the instrument makers' expert knowledge and skills, but above all on the quality of materials, without which high-standard musical instruments could not be crafted [473]. Thus, manufacturers of musical instruments require access to a large variety of natural materials from animals and plants, especially wood [121]. Following historical European expansion and international trade fueled by the colonial era and ongoing globalization, European musical instrument makers have made use of access and materials from species that originate from distant ecosystems around the world and local environments alike [310]. Uncontrolled overexploitation of natural resources worldwide is responsible for endangering a multitude of threatened species and ecosystems, increasing the threat to traditional musical instrument making, an intangible cultural heritage that preserves valuable traditional craft knowledge [165]. This precarious ecological situation and cross-cutting culture calls for novel strategies to preserve our "global orchestra ecosystem".

The emergence of global perspectives on the interrelation between nature and music poses a challenge to the preservation of both [109]. The global loss of significant cultural and natural heritage originates mainly from a profound lack of awareness and understanding of the interlink-age of threats to music, musical instrument making, and distant ecosystems. Lichtenberg, Huber-Sannwald, Reyes-Agüero, Anhuf, and Nehren [269] recently proposed an integrative framework to examine these telecoupled cultural-ecological systems from a conceptual and empirical perspective to develop long-term sustainable solutions to this complex challenge. The following elements need to be taken into account: materials used for instrument making, their visual appearance, the plant and animal species and their habitats, the species' current and historical ecologically grounded threat levels, international trade regulations, as well as their population trends.

Our project is the first to tackle these multidimensional interdependencies and make them visible so they can be explored. In addition to visualization scholars, our Co-creation Team consisted of a violin maker, geographers, biologists, and an ecologist. The merge of these domain expertise and specific research perspectives set the stage for an overall enhanced understanding of the unexplored interrelationships. Through a participatory and iterative design process [203], we collectively designed *MusEcology*, a web-based visual analysis platform, addressing the following main objectives:

- **Visual metaphors** to symbolize the ecological and trade-related threat status for single species and sets of them via glyphs.

- A **linked views design** tailored towards complex data sets with information on musical instruments, natural materials of plant and animal species, their associated threat status, and geographical distributions.

- A **multi-layered geospatial design** that allows investigating the distribution of terrestrial and marine species considering political (countries) and ecological boundaries (biomes, ecoregions, approximated species distribution).

- A **species timeline** particularly designed to demonstrate the development of ecological threats and trade regulations of species.

- A **target-user driven design approach** to make the system as a whole accessible and comprehensible for users with a non-technical background.

We further present two use cases that exemplify the value of the *MusEcology* platform for users of different domains. In addition, we report on informal feedback from domain experts, using *MusEcology*, commenting on its inter- and transdisciplinary potential. Finally, we acknowledge certain limitations and discuss future extensions of the platform.

4.2.2 Related Work

Our interdisciplinary approach results in a multi-modal set of used resources, data types, and attributes. It calls for appropriate visual representations of individual dimensions and a sophisticated interaction scheme among them to communicate the complex interrelations accordingly. We bear on related works on visualizing hierarchical, temporal, and geospatial metadata and deploy a coordinated views system to allow for a multifaceted exploration of our data set.

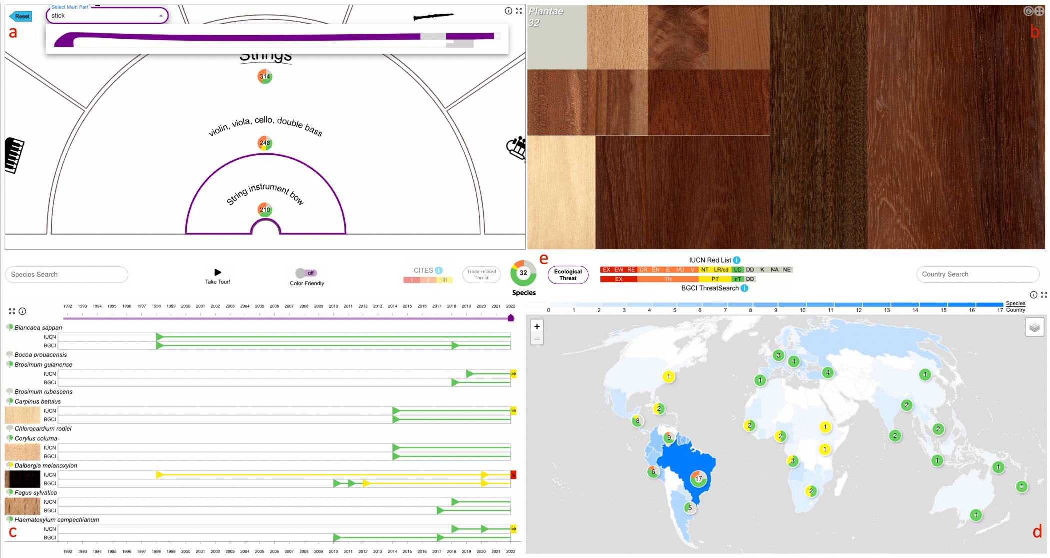

Figure 4.1: *MusEcology*: Overview of the platform and its interconnected components. The stick of a string instrument bow is selected in the Orchestra View (a). The plant species used to produce the stick are depicted in the Material View (b). Their threat history is contextualized in the Timeline View (c), and the Diversity Map shows their geospatial distribution (d). All the views are connected through a consistent color and glyph design (Legend, Threat Donut, and Threat Icon) and search and filter functionalities (e).

Hierarchical Views The taxonomy of the different species in biology is hierarchically organized and forms a tree-like structure. This taxonomy is mostly represented by a tree visualization [184, 268]. The treemap is another possibility for the representation of hierarchies [208]. Thus far, we are unaware of an existing implementation of a treemap used for matching materials to a biological taxonomic classification scheme. However, an approach exists that represents the species hierarchy as a Voronoi treemap [176]. Also, musical instruments can be classified by a taxonomy. This taxonomy can then be represented interactively as a tree [98]. We also adopt a 180 degree sunburst chart [476] that replicates an orchestra's hierarchical arrangement of instruments. Related visual depictions are provided for musical pieces performed by the London Symphony Orchestra [274] and for the progression of an orchestra's sound [308].

Temporal Views The visualization of time-based data is subject to many applications. An overview of different strategies for presenting time series data are discussed by Aigner, Miksch, Schumann, and Tominski [4]. An everyday use of time series is the comparison of attributes over a period of time. Different studies [132, 169, 206, 425] provide recommendations for the visualization depending on the use case. Particular domain-specific usage scenarios of timelines that relate to our focus on threatened species include the CITES Checklist [64, 468] or temporal relationships between musical instruments and musical pieces [252]. Although we lean on the existing design to create some familiarity, we juxtapose diverse information for each species and enhance the visual design with newly created glyphs and icons to combine the different data sets.

Geospatial Views Andrienko and Andrienko [9] proposed a taxonomy for mechanisms to link multiple displays of geospatial data. An essential aspect of their taxonomy is a "display coordination based on a subset selection", e.g., multiple displays show information about a chosen subset of the data. They are linked by highlighting, zooming, and filtering mechanisms so that an interaction in one display is also reflected in the other displays. If certain areas in the map should represent a particular value, e.g., the population density of a specific species, choropleth maps are often used for the representation [96, 195, 309]. Suppose an artificial grid dividing individual areas hexagons can be used for tiling [298], since with hexagons the distance between two tiles can be determined more easily than, for instance, with squares. Furthermore, global forest loss is visualized [440] or the habitats of selected species are presented geographically [148, 205, 417, 421]. In addition, Annanias, Zeckzer, Scheuermann, and Wiegreffe [11] have shown how human impacts have reused land. Next to heat maps, Gixhari, Dias, Hodaj, Ismaili, and Vrapi [145] design various glyph-based maps to communicate diverse aspects of fruit tree species distributions in Albania. Reckziegel, Cheema, Scheuermann, and Janicke [355] discuss the usage of tag maps to display the distribution of tree species that is limited when only using text and color by displaying the most common species in an aggregated spatial area [372].

Multiple Coordinated Views Wang Baldonado, Woodruff, and Kuchinsky [445] proposed multiple coordinated views to reduce cognitive overhead compared to a more complex single visualization. However, they also note that this approach can impact the training time to use this visualization. We try to reduce this by using visualizations used by the application domain (maps, timelines) and combining them with visualizations we designed specifically for the use case (Material View with veneers and Orchestra View) to lower the hurdles and create entry points into the complex topic. Gleicher [146] and L'Yi, Jo, and Seo [257] have also evaluated which approaches to specific use scenarios are recommended for multiple coordinated views. Based on their recommendations, we use a chart-wise juxtaposition, where in the different views, various attributes of the data are displayed for a comprehensive analysis, representing the same set of selected species. This paradigm has also been used to visualize musicology data. For example, Khulusi, Kusnick, Focht, and Jänicke [222] used a combination of timelines, maps, and sunburst representations to connect information on musical instruments and their makers. Moreover, this paradigm is also used to visualize biodiversity data [27, 204, 401]. Usually in combination with a map, for example, timeline data and taxonomy of species are displayed in a linked fashion to support understanding of the distribution of birds [119] or species in the European Red List [194].

To our knowledge, we are the first to combine and visually process data from the economic and ecological fields with musicology. Only UNESCO Intangible Cultural Heritage partially addressed this issue regarding intangible cultural heritages, including traditional musical instrument crafts and their multidimensional threats. Ecological factors, such as species threat levels, have a significant impact, among others, on instrument making and need to be brought into context. For their understanding, necessary visual representations of these interconnections of topics, as well as meta-information on musical instruments in general, are missing [224].

4.2.3 Background and Task Description

Several musical instrument making crafts and musical traditions have been declared Intangible Cultural Heritage by the United Nations Educational, Scientific and Cultural Organization (UNESCO) [345]. At the same time, many natural materials used for making musical instruments originate from animal and plant species [121] found in natural heritage sites, thus connecting cultural and natural heritage across borders and great distances [269]. To determine and characterize such cultural-ecological interconnections, all instrument parts derived from plants and animals need to be identified at the species level (taxonomically verified) and linked to their natural distribution. A careful selection (type and quality) of these natural materials is essential as this is directly linked to the quality of musical instruments, i.e., referring to critical acoustic, physical, and haptic criteria. Material quality, in turn, is often directly related to geographic location and several biophysical characteristics, such as temperature, precipitation, soil type, and habitat quality. A classification of the origin of species according to such ecological criteria is possible by defining ecological boundaries for areas, taking into account at least one of the boundary characteristics, such as origin and conservation, spatial structure, function, or temporal dynamics [406]. Ecoregions define ecological boundaries according to a biogeographic classification system based on the distribution of a range of animal and plant species across the planet and include representative habitats and species communities within biomes [333]. Biomes describe the global large-scale distribution of ecosystems consisting of different ecoregions encompassing large regions with similar vegetation and climatic conditions [429]. But also, the visual appearance can influence the value of instruments and confers to the material's uniqueness, rarity, or exoticism.

Since 1964, the "International Union for Conservation of Nature" (IUCN) has been listing species in its Red List and categorizing their threat risk using standardized criteria [421]. The 'Botanic Gardens Conservation International's (BGCI) ThreatSearch' collects similar assessments and provides them on their website [41]. Species' threats can be considered at and delimited to certain ecosystems, which are classified into biomes and ecoregions [333], as well as to socio-economic and socio-political contexts.

Globalization has dramatically contributed to biological and cultural diversity loss, severely impacting human societies [52]. The main causes of ecosystem loss and degradation are overexploitation of natural resources and land-use change, significantly reducing intact ecosystems, thereby threatening many species worldwide [130]. For an increasing number of species commercial uses, selective exploitation and international trade pose direct threats to their survival; therefore, trade of these species is regulated internationally [29, 51], by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). These trade restrictions are necessary but also affect the availability of raw materials for instrument making.

The direct interconnection of cultural and biological diversity through material use for musical instrument making and its reciprocal influence on their common threat becomes apparent in the context of musical instruments and profoundly visible through *MusEcology*. Emerging future challenges for nature and culture are continuous forest loss, land-use changes, and the impact of climate change on ecosystems. These processes together increase the pressure on species used for musical instruments and, consequently, on the musical instrument making crafts and, subsequently, on music traditions.

The visualization of this multidisciplinary, interwoven, complex topic shall support decision-making processes by providing an overview of all described aspects, their interconnections, and certain detailed information resulting in these domain-specific tasks:
T1: Show the importance of music traditions as intangible cultural heritage.
T2 - *mapping*: Establishing overview of the mapping of musical instrument parts (instruments and their instrument groups) to the species used as natural materials.
T3 - *distribution*: Geographically locate the species distribution indicating the number of species per region (species richness) in countries, ecoregions, and hexagons.
T4 - *appearance*: Conveying insight into the visual appearance of natural materials and their biologic taxonomical hierarchy.
T5 - *ecological threat*: Using threat assessments (by IUCN and BGCI) to estimate the ecological threat to each of the species.
T6 - *ecosystem threat*: Inform about threats to ecosystems and biodiversity to evaluate the stress and regeneration potentials.
T7 - *trade*: Reference to trade regulations by CITES as an indicator of pressure on species, trade restrictions for culture, but also as conservation measurement.
T8 - *context*: Providing temporal and geo-spatial context of regulations and threats and population trends to evaluate historical and current status to support future decisions.

4.2.4 Methods

The development of *MusEcology* is based on an iterative, participatory design process that encompassed several stages of transdisciplinary elaboration in the form of a nested team model involving six key domains (visible in Figure 4.2) and their related data sets (see Figure 4.3). The Core Team designed and implemented the database, visualizations, and web application in form of a design by immersion [159]. Thereby domain design aspects, supervision, and early feedback were provided through continuous internal evaluation and feedback loops by the experts from the Co-creation Team. We emphasize the balanced gender ratio in these two teams (Core Team, Co-creation Team), whereby further details about the composition of the External Experts are described in Subsubsection 4.2.6. The collaboration between Core Team, Co-creation Team, and the External Experts followed a participatory visualization design process [203]. Part of this design process was the continuous selection, combination, and new linkages of open-access domain-specific data repositories; this opened new venues to create and visualize unexplored interrelated knowledge and discover new research fields. As a result, our data sets and functionalities keep growing and developing throughout the design process by including expertise via new data sets and project partners.

Data

To display the complex interconnections described, the incorporated data combines different repositories and sources, which we describe below. For species used for materials to build musical instruments, we used data sources that consider their threat status in an ecological context and an understanding of trade-related restrictions. Regarding both aspects, we focus on the species level by considering political as well as ecological borders as described in the section on spatial information. From a biological perspective, the risk of extinction is an important measure to be considered

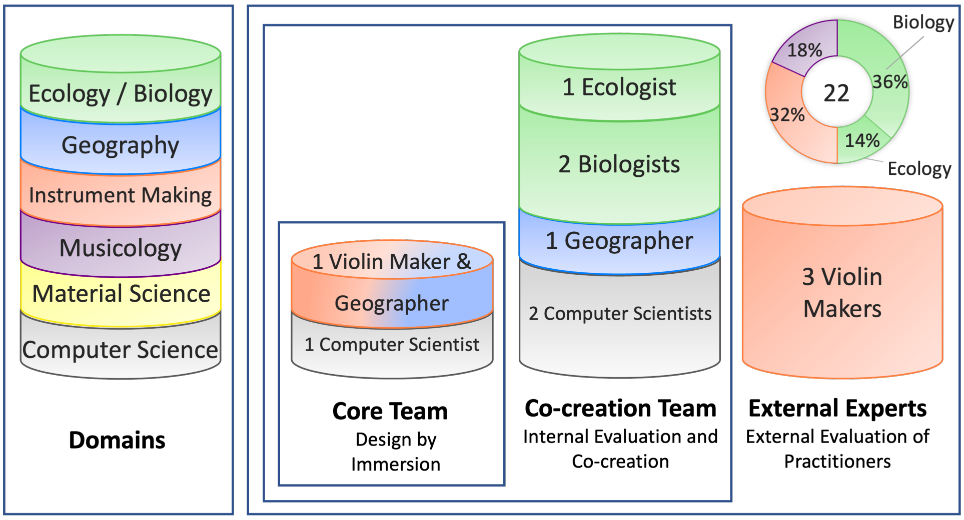

Figure 4.2: With the underlying nested team model, relevant domain experts were incorporated into the participatory visual design process while maintaining the viability of the platform development. Each color-coded slice stands for six key domains and their expert(s): instrument making (red), musicology (purple), ecology/biology (green), geography (blue), material/wood sciences (yellow), and computer sciences (white). All domain experts contributed to the project with data and knowledge from the respective teams.

for species used for musical instruments. From an economic perspective, an important measure is the legal trade ability, availability, or scarcity of every natural material used for musical instruments deriving from plant or animal species. Our whole design approach focused on the global level with embedded local processes and foci.

The complete **description of species in our data set** is defined as:

$$s \in S = \begin{pmatrix} g, & \text{genus} \\ f, & \text{family} \\ k, & \text{kingdom} \\ P, & \text{set of instrument parts} \\ A^{CITES}, & \text{set of CITES assessments} \\ A^{IUCN}, & \text{set of IUCN assessments} \\ A^{BGCI}, & \text{set of BGCI assessments} \\ H, & \text{set of hexagons} \\ E, & \text{set of ecoregions} \\ C, & \text{set of countries} \end{pmatrix} \tag{4.1}$$

Materials for Musical Instruments

We focused on the materials used for musical instruments of symphony orchestras representing the classical music culture. We consulted 17 literature sources in wood and material sciences [10, 29, 50, 56, 57, 58, 340, 364, 449, 450], instrument making and online supplier for parts of instruments [104, 192, 307, 339], and possible materials used in the case of reference only mentioning a genus or common name [42, 104, 436] to find out the type(s) of material(s) used for musical instrument parts and the corresponding taxa. We created two major hierarchically structured data sets as the foundation.

The first is a nested hierarchy based on the following assumption that an orchestra O can be divided into:
(1) multiple instrument groups IG, therefore, applies $O = \{ig \in IG\}$, where (2) an instrument group consists of instruments I with shared characteristics $ig = \{i \in I\}$, and (3) an instrument is built of instrument parts P, described as $i = \{p \in P\}$. Specifically, instrument groups of an orchestra are $ig \in \{Strings, Keyboard, Plucked, Woodwinds, Percussion, Brasses\}$. In addition to the typical orchestra instruments, we considered the guitar, bagpipe, cembalo, and recorder family to include other popular musical instruments.

The second domain set relates to the natural materials used to manufacture musical instruments. We created a database linking instrument parts of each musical instrument and the species origin of materials used. So that the instrument parts are defined by several species $s(P) = P = \{s \in S\}$. Species are the lowest level of a biological taxonomic system that we are considering; thus, it has a clear assignment to a genus $s(g) = g \in G$, family $s(f) = f \in F$, and kingdom $s(k) = k \in \{Animalia, Plantae\}$. We can use the above-listed assumption recursively so that the instrument group is also "consisting" of species $IG = \{I\} = \{P\} = \{S\}$.

In total, our database includes 5,965 assignments for six musical instrument groups, 39 musical instruments, and 65 different main parts of musical instruments; they are assigned to 758 species (60 animals and 698 plant species), 286 genera, and 113 families. We merged instrument families and musical instruments made of the same components into a single group if the same materials can be used for their construction, such as all string instruments, while, e.g., the string instrument bow is listed separately as its own instrument, because it consists of different parts and materials than string instruments.

Species Threats

Different assessments exist for animal and plant species that determine the risk of species extinction on a global scale. Independent of this, but taking this risk into account and depending on the cause of the threat and political interests, decisions are made on necessary trade regulations and the extent of restrictions to prevent their extinction.

The threat state, or the extinction risk of each species at a global level, is scientifically assessed and then published. Our decision support system can be described by a tuple of necessary information specifying the assessed category of threat state a_c and the publication year a_y; for now, we are only focusing on global assessments. So, the set of all historical and most current assessments of a species s can be noted as $s(A^*) = \{(a_c, a_y)\}$. Whereby A^* stands for a set of assessments from one source $\in \{CITES, IUCN, BGCI\}$, which are described in the following sections.

Ecological Threats The IUCN Red List provides information on the range, population size and trend, habitat and ecology, use or trade, threats, and conservation actions and indicates the health of the world's biodiversity [421]. However, other assessments of global scope evaluate species similarly and categorize their threat risk. The "BGCI ThreatSearch" collects these different assessments for plant species, including those of the IUCN Red List [41]. For each species used for musical instruments, we identified the respective species-specific threat status considering the listings of the database of the IUCN Red List and the listings in the BGCI ThreatSearch as well as their changes in threat status at the global level over time, creating the sets $s(A^{IUCN})$ and $s(A^{BGCI})$.

Although both repositories use their categories to describe the threat levels, they stay comparable by the BGCI ThreatSearch mapping [41]. For example, "Possibly Threatened" (PT) is mapped to both IUCN Red List categories "Near Threatened" (NT) and "Lower Risk/Conservation Dependent" (LR/cd). Thanks to this system, the various categories are also sort-able so that we can decide on the strictest BGCI ThreatSearch assessment because there can be multiple listings in one year $strictest(s(A^{BGCI})) = argmax\ s(A^{BGCI})$.

To obtain one summarizing statement for the ecological threat of species, we group the assessments of the IUCN Red List and BGCI ThreatSearch and decide according to the following procedure. The assessments by the IUCN Red List are the most widely used sources internationally and are included in the BGCI ThreatSearch. We use the *latest* IUCN listing and the *latest* assessment of ThreatSearch if the species is not listed in IUCN. Taking the example of *Manilkara longifolia* at the global scope, in 1998, it was listed as "endangered" in the IUCN Red List; in 2011, BGCI ThreatSearch shows its listing as "not threatened", which would be the *latest* listing. But as we prioritize the IUCN Red List listing, we depict the summed threat as "endangered".

$$s(threat) = \begin{cases} latest\big(s(A^{IUCN})\big), & \text{if } |s(A^{IUCN})| > 0 \\ strictest\Big(latest\big(s(A^{BGCI})\big)\Big), & \text{otherwise} \end{cases} \tag{4.2}$$

Trade-related Restrictions At the global scale, regulation of trade between countries and across continents of materials from endangered species is of utmost importance and the task of CITES. The agreements on trade restrictions decided by CITES are legally established and implemented by each member state; they are based on the findings that economic trade of the species in question contributes significantly to its threat. Therefore, for the trade-related threat, we considered the species-specific listings in CITES by consulting the Species+ database [64] and their changes over time $s(A^{CITES})$. Whereby the *latest* CITES listing in history is the actual state of trade regulations in our system:

$$s(trade) = latest\big(s(A^{CITES})\big) \tag{4.3}$$

Materials' Appearance

Visual criteria are essential for distinguishing materials and play an important role in selecting materials for musical instruments. The material appearance of tree species is made accessible by 174 assigned photos of the extraordinary Mautz wood collection of the Thünen Institute Hamburg and 35 photos of animal and plant species derived from the personal photo collection of Silke Lichtenberg. All photos are linked to the respective species in the database of materials of musical instruments. For species without existing photos in the collections, we manually selected similar-looking species' material within the same genus as a proxy photo of the available images.

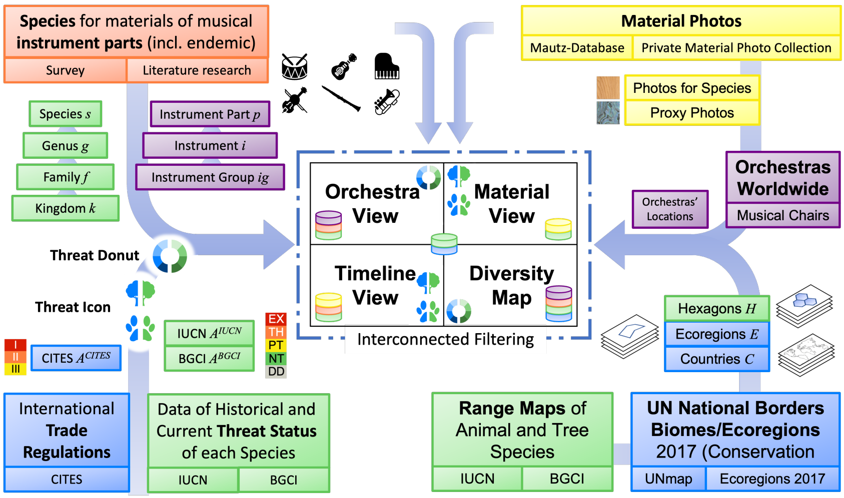

Figure 4.3: An overview of the diverse data repositories linked to our six key domains: musical instrument making (orange), ecology/biology (green), geography (blue), material/wood sciences (yellow), musicology (purple), computer science (white) and merged to depict four different interconnected views: Orchestra, Material, Threat Assessment Timeline, and Diversity Map. This visualizes the transdisciplinary contributions of the mentioned domains and the complex interrelations among the four views representing critical characteristics of a global orchestra ecosystem. The strong connection of ecology and geography to the other domains is symbolized by the use of Threat Icons and Threat Donuts within the visualization views. This tool can answer specific questions of interest related to one or more domains. However, with the visualization of the interlinked views, a novel learning environment can be generated, as well as innovative research questions posed and research gaps discovered.

Spatial Information

We are interested in spatial information available in different data types to give insight into the global diversity and distribution of species used for musical instruments. We received point distribution data sets for 360 tree species from the "Botanic Gardens Conservation International" (BGCI) [42]. Additionally, we downloaded 28 available animal species distribution maps from the International Union for Conservation of Nature and Natural Resources (IUCN) Red List webpage [421]. To cluster and homogenize these distribution maps for all species, we binned the point datasets of BGCI and intersected the polygon datasets of the IUCN Red List to an artificial global hexagon raster, where each hexagon corresponds to approximately 1000 km² $s(H) = \{h\}$. To create an ecological habitat understanding, we embedded the species distribution to terrestrial ecoregions $s(E) = \{e\}$ [96].

As international trade regulations are implemented at a country level, we used the countries listed for each species in the BGCI TreeSearch [42] as well as the countries listed in the IUCN Red List database to map species richness at the country level $s(C) = \{c\}$. We synchronized the given country names with the country borders published by the United Nations (UN) [181].

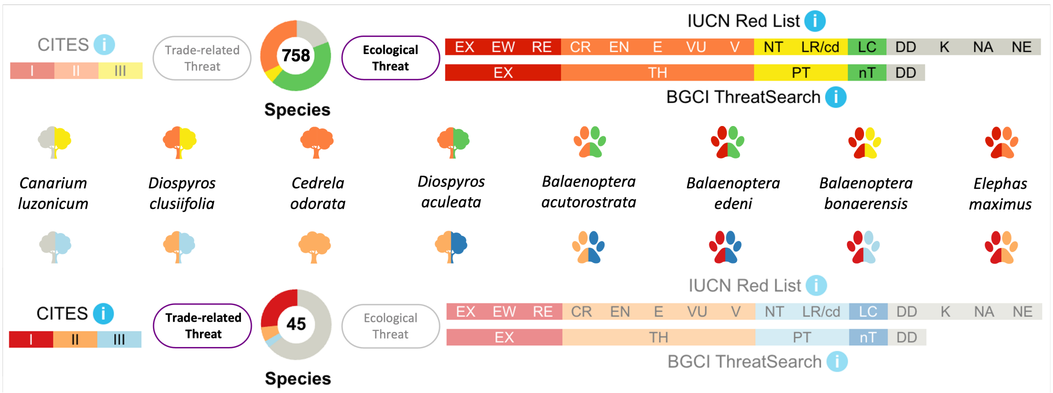

Figure 4.4: The top two rows show the species glyphs (Threat Donut and Threat Icon) and color legends in default color mode, and the bottom two rows are in color-blind friendly mode. The traffic light color-coding for the categories of the IUCN Red List, BGCI Threat Search species assessments, and CITES listings is explained by the Color Legends. Threat Donut: The Threat Donut is a central part of the legend and is depicted in the orchestra view and the diversity maps. It always symbolizes the combined threat (trade-related or ecological) of all species in the current selection for either. It depicts the most recent ecological or trade-related threat assessments for selected species. The aggregating Threat Donuts show the overall threat distribution considering the number of species in the selection (e.g., instrument group, instrument, country or taxonomic group, etc.), either related to trade-related restrictions/threats or ecological threats (see purple framed legend labeling). The Threat Donut on top represents the ecological threats of all 758 species, and the bottom encodes the trade-related threat/restrictions for selected 45 species. Threat Icons: the Threat Icon (the two middle rows) is only depicted on a species-specific level, not for a group of selected species, and always shows the trade-related threat linked to CITES on the left and the ecological threat on the right.

4.2.5 Visual Design

In this section, we explain our visual design approach for the visualization of the collected and combined interdisciplinary data repositories by starting with a description of how they were merged and which domains are addressed in which part of the visualization, as well as a description of which design decisions were taken and why. We continue describing the assumptions, aggregations, and interactions to the details of specific visualization elements.

The result of this process was *MusEcology*, a web application using JavaScript libraries such as React [354] for the overall architecture, Leaflet for the map, and D3.js [40, 80] for other visualization components, forming four interactive and interconnected views that offer an intuitive entry point for users of different disciplines opening up insights into them, as schematically shown in Figure 4.3.

System Design

The desire to include **Interconnected Filtering** throughout *MusEcology* as the core of our design originates from the goal of this application, intended to strengthen the complex system's understanding, where all elements are connected and by changing one aspect in the system all other factors are directly or indirectly influenced. Each visualization view can be accessed and used to explore and analyze various topics. They are linked by reoccurring visual elements as summarizing glyphs: the **Threat Icon** of the pressure on single species (**T5, T7**) and the **Threat Donut** encoding status overviews of sets of threatened species (**T5, T7**).

Interconnected Filtering All visualizations are based on a set of species, and they are generated through a faceted filter process defined by user interactions considering all four visualization views and other user interface elements. Clicking an interactive element activates the faceted filtering regarding the corresponding data dimension, and the rest of the interface updates accordingly because the filter is applied in all views on the overall used resulting species subset. Thanks to the described variety of data dimensions of one species s, we allow the intersected filtering by:
(1) biological taxonomy $\left(s(name), s(g), s(f), s(k)\right)$,
(2) use in the orchestra $\left(s(P), s(I), s(IG)\right)$,
(3) geospatial distribution $\left(s(C), s(E)\right)$ and
(4) threat level $\left(s(A^{IUCN}), s(A^{BGCI}), s(A^{CITES})\right)$.

The application then filters the species set according to the selected attribute values where the conjunction of all filter settings is used. The selections within the views are highlighted by outlines in a purple color like shown in Figures 4.1, 4.5, and 4.6 because this color is not used in the rest of our color pallet.

Threat Icon The design decision for a threat icon that appears in the different views originated from the feedback of the domain experts pointing out the gain of information when including one single threat icon that easily allows the classification of the threat situation (**T5**, **T7**). During the process of trying to implement such an icon, we detected that it is not possible to transparently combine trade-related restrictions and threats (CITES Trade regulations) and ecological threats (IUCN Red List/BGCI ThreatSearch) in one icon without losing the original information of the data repositories. Therefore, we developed the two-part tree and paw Threat Icons presented in Figure 4.4. It combines trade-related threats ($s(trade)$) on the left half and ecological threats ($s(threat)$) on the right half and symbolizes with its coloring the most recent threat levels. Without an assessment, we symbolize the missing knowledge by the gray color for “Data Deficient”. A tool-tip explains this compound threat icon when users move the mouse cursor over a Threat Icon in the Timeline or Material View.

The coloring for assessments in our visualizations is derived from the color pallet used by the IUCN Red List for their assessment categories. Whereby we color-matched the categorizations of the IUCN Red List and BGCI ThreatSearch according to BGCI ThreatSearch mapping, as described in paragraph 4.2.4 and shown in Figure 4.4. The color coding for the CITES listings follows an analog logic: the stricter the regulations, the more threatened the species must be by trade, and the more significant the potential negative impact or threats to the traditional craftsmanship of musical instrument making due to materials scarcity. As our traffic light colors for the various threat levels are significantly based on the contrast of red, orange, yellow, and green, we enabled an optional color pallet through an interface switch for a more color-blind friendly mode. Therefore, we tried to find suitable and matching colors by using the online tool ColorBrewer [162].

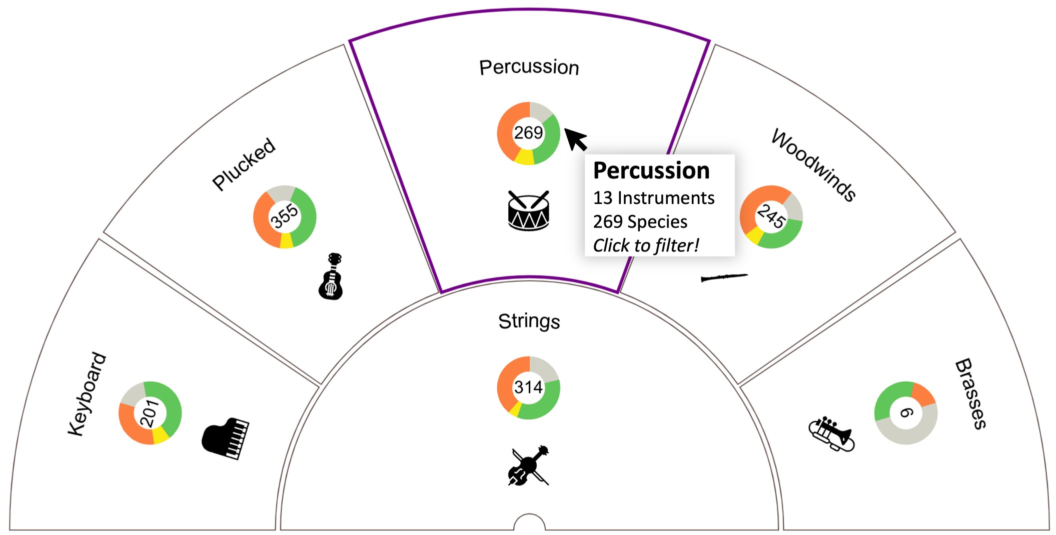

Figure 4.5: Outlines in purple highlight the selection of an instrument group within the Orchestra View. Each instrument group is symbolized by a slice within the schematic orchestra and a musical instrument icon to enable the visual entry point into the nested hierarchy of instruments and their parts. The ecological or trade-related Threat Donut inside each orchestra slice refers to the average threat status of the total number of species used for a particular instrument group.

Threat Donut By using the most recent states of the Threat Icons, we can derive a glyph for a whole set of species ($\{s_n\}$) as an aggregation in our interface. During our iterative process, we discovered that a one-colored icon of hierarchically upper levels, such as instrument groups or countries, would oversimplify the complexity and lead to unjustified generalizations regarding the selected species' threat status. To address this problem visually, we decided to use a donut chart showing the distribution of different threat levels by colored ring segments and the number of species ($n = |s_n|$) depicted in the center of the screen to show an estimation of the whole current selected set of species. For example, we can draw the ring segment for the occurrences of Appendix I listings by CITES of all the species in our scope (n) by using its cardinality as measurement for the size and the mapped color (in this case red) ($|\cup_{i=1}^{n}\{a \in s_i(trade)|s_i(trade)_c = \text{Appendix I}\}|$). We are using a switchable mode to either focus on trade-related threats (**T7**) or on ecological threats (**T5**), allowing to change between two different appearances of each Threat Donut. We pick up the Threat Donuts in our Orchestra View (see Figure 4.5) to depict the threat level distribution and the number of species used for single instrument groups (**T2**). We also convey the threat information to geographical regions (**T3, T8**) in the Threat and Diversity map (see Figure 4.6).

Visualization Views

Since the combination of the complementary, equally important information and all interconnections among them build the core of the *MusEcology* platform, we decided to divide the monitor into four equal-sized visualization views, including: a schematic **Orchestra View** of natural materials used for musical instruments in an orchestra, the **Material View** treemap displaying the taxonomy and visual appearance of them, the geospatial distribution in the **Diversity and Threat Map** and temporal progression of species threats in the **Timeline View**.

Orchestra View For the world of musical instruments, the symphony orchestra is our scope, thus we chose a schematic structure of a simplified classical orchestra with instrument groups organized around the conductor and its underlying hierarchy as described in Subsubsection 4.2.4. We decided for a domain specific design although it creates substantial whitespace compared to other selection methods. We want to lower the hurdles and enable experts of domains such as instrument making or musicology to find recognizable symbolics as entry points into the system and complex topic, and since the symphony orchestra symbolically represents the classical music world (**T1**) it arouses curiosity from users of disciplines not connected to music. We present instrument groups by matching icons and symbolize the summary of used species within the groups (**T2**) by their diversity of threat levels (**T5, T7**) in form of the switchable Threat Donuts (see Figure 4.5). Thereby the set of species within an instrument group is $\{s_i\} = \{P\} \in \{I\} \in \{IG\}$. Clicking on individual instrument groups zooms in (also in the viewport), filters the dataset for species used in this instrument group and reveals the underlying instrument list (see Figure 4.1a). Within the list of instruments, it is also possible to focus on one single instrument by clicking, and a selector for the underlying instrument parts appears. In contrast, neighboring instrument groups remain visible in the zoom viewport. Suppose a schematic construction plan of an instrument is available in our database. In that case, users can visually select the instrument part instead of the textual selection in the dropdown menu as shown for the string instrument bow in Figure 4.1a.

Material View Including a view focusing on the natural materials used for musical instruments and their visual appearance (**T2**) allows us to link them with ecosystems from which the species stem. We make these central elements and their appearance (**T4**) directly visible while highlighting their taxonomic rank by showing their photos within a zoomable, rectangular treemap. Similarly to the Orchestra View, this view contains all species in the actual selection. It follows in its zoom levels the hierarchical taxonomic classification system as described in Subsubsection 4.2.4. For example, the default and most coarse level of the Material View is created by the division of species in their kingdoms, either animals or plants $s(k) = k \in \{Animalia, Plantae\}$ including corresponding family, genus and species sub-groups. The size of each group rectangle is defined by the number of the species in it $|s \in k|$. We also use cardinality for sorting the groups, so neighboring cells in the Material View are not phylogenetically closest to each other. Whereby we prioritize the entries with lower amounts of species to the top left because, during our evaluation rounds, we experienced that these sets of species were overlooked at the utmost right edge of the screen. A preview of the underlying next zoom level is shown in one group rectangle. Thereby, each sub-group is symbolized just by the photo of the predominant, the most common species, to avoid visual clutter. A click on each group is zooming in and filtering the whole set of species accordingly across the entire system. On top of the Material View, we indicate the actual selection within the hierarchy by a table, stating kingdom, family, genus, and species (see Figure 4.6), which are also used to move up in the hierarchy again by clicking. When single species are apparent, like in the case of the genus or species group overview, the matching species Threat Icons (**T5, T7**) are annotated in the bottom left corner of the rectangles (see Figure 4.6). But we decided against an overlay of threat pies within the Material View itself to keep the view free of further distractions. The proxy photos for species without an actual image are distinguished through a semi-transparent gray overlay and the text "proxy" on top of it. For users who wish to directly access the information of certain species, we also implemented a search bar for single species and genera, which filters the species directly for names.

Diversity and Threat Map The species richness and threat map is a central part depicting all interconnections in a spatial context to quickly locate the distributions of species – the origins of materials used for musical instruments within different kinds of regions. Our map's regions can be countries, terrestrial ecoregions, or hexagons, depending on the selected semantic zoom level. To show the richness and spatial distribution (**T3**) of the selected species, we map the number of species in regions on an interactive and zoomable choropleth map. For example, the diversity in a country c is given by the different species found there ($|\{s \in S | c \in s(C)\}|$), and can be symbolized by the underlying blue intensity (heat map), the more intense the color, the more species appear in that polygon. The regions are also connected to the trade-related restrictions (**T7**) and the ecological threat status (**T5**) by overlaying Threat Donut charts (**T8**). The combined visualization of species richness and threat level captures elements also determined for the earlier mentioned biodiversity hotspots (**T6**), although in our case, limited to species used for musical instruments occurring per country, ecoregion, or hexagon. The placement of Threat Donuts within the map corresponds to the country level, the location of the countries, capitals, and, in the cases of ecoregions and hexagons at the geometrical center of the ecoregions. The clustering of the donut charts is implemented by an extension "Leaflet.markercluster" [261] to avoid overlap by grouping neighboring Threat Donuts and merging their existing species. Framing of the areas clustered in a donut chart is revealed through a mouse hover using the purple highlight color for the bordering lines. We decided on the Mollweide projection, being a good compromise between an equal-area projection to adequately represent the Global South and to meet the aim of an appealing map design, consistent with the findings of Leon, Lischka, and Breiter [**citeauthor {Leon.2008}**]. Depending on the mode of the map, the users can search for countries, ecoregions, and their associated biomes by name. At the same time, they are supported by autocomplete recommendations to facilitate a fast target-oriented use of *MusEcology* via the search bar.

An additional layer of the map does not follow all design decisions but complements the Orchestra View, focused on the musical instruments and their parts, by showing the distribution of classical orchestras (with all their instruments) worldwide by their geolocation which opens another perspective for the musicology domain (**T1**). This orchestra distribution layer in combination with the species richness maps illustrates the understanding of a meta-coupled cultural-ecological system. All orchestras are embedded in different local ecosystems through their locations around the world and are interconnected through the materials used for their instruments (**T2**), which are sourced from various species from diverse ecosystems around the globe. Here, the donut charts are filled by the purple highlight color, and the diversity heat map in the background encodes the number of orchestras per country in blue shades (Figure 4.7).

The second additional map layer is the "Ecoregion Protection Potential" showing a future perspective on the potential of each ecoregion for reaching half of its area being or becoming a protected area (**T6**), which is based on the results of Dinerstein et al. [96]. Increasing the size and number of protected areas is considered an essential strategy to preserve biodiversity, counteract the mass extinction of species, and contribute to climate change mitigation. We are reusing the polygon layer of ecoregions to unveil their potential to be protected by color coding corresponding to our color map of threat levels (see Figure 4.7).

Timeline View The investigation of historical and present threat assessments originates from a complex system's understanding; it assumes that to determine the current situation, it is necessary to consider past developments and changes to estimate future effects (**T8**). To communicate these changes in threat status over time, we developed a Timeline View, listing every species' ($s_i \in \{s_1, ..., s_n\}$) threat development in a single row. Whereby we introduce the row of s_i by a thumbnail image of the material to convey a first impression of the visual appearance (**T4**). In the following, the history of all available listings of the species is divided into sub-rows (**T5, T7**) regarding their source ($a \in s(A^*) = \{s(A^{CITES}) \cup s(A^{IUCN}) \cup s(A^{BGCI})\}$). Due to the diversity of their processes and assertions, we decided against aggregating the assessment throughout the three repositories at this place and chose a juxtaposition. Since the assessments are done at a certain point in time, they can explicitly reflect the actual status only in the assessment year (a_y). The uncertainty about the subsequent dynamics is why the individual assessments are symbolized by triangular glyphs pointing to the right, located in the timeline according to the year of the publication. Until a new assessment is made, the threat status is depicted by a line showing that the last historical assessment remains the reference for the species. However, its accuracy was only assured in the year of publication.

We use tool-tips in the timeline revealing the details by hovering over the single assessments arrow glyphs or the population trend at the end of the IUCN Red List's sub-row. This population trend is assessed by the IUCN Red List [420] and is used by us for reasons of accuracy and to counteract false interpretations of the previous assessments (**T8**). We use the same traffic light color coding for the four possible states: increasing, decreasing, stable, and unknown.

Through the time-slider above, the upper border of the actual species threat status reflection can be set, so that the assessments are filterable by this upper border of the time frame to display the *latest* states in a decent historical point in time. For example, with the year filter set, the following applies to CITES: The trade (left) part of the Threat Icon, according to the last CITES listing before a given year i is described by

$$s(trade_{y=i}) = latest\big(\{a \in s(A^{CITES})|a_y < i\}\big). \tag{4.4}$$

We decided on a one-sided slider, just filtering at the upper border of the time frame because the last assessment in history is determining the actual status, which is also indicated by *latest* in our formulas. The assessments after the selected year are still visible but grayed out, and the species icon is adjusting accordingly to the last assessed states within the time frame. By moving the slider, the user can also inspect the historical development of threat states in other visualizations, where aggregations such as the recurring species Threat Icons in the Material View are also updated according to the selected time frame.

Figure 4.6: Left: Detailed view of the wood appearance of *Paubrasilia echinata* with the table indicating the selected kingdom, family, genus, and species. Left: map with *Paubrasilia echinata's* hexagon distribution along the coast of Brazil. The tree Threat Icon entirely in orange indicates the trade-related threat (left half) - a listing in CITES Appendix II - and the ecological threat (right half) - being a species categorized as endangered. The orange Threat Donuts in the map indicate with the number 1 that only one species is selected and depicted in the hexagons - (*Paubrasilia echinata*) - which is endangered and listed in CITES Appendix II, depending on the chosen mode (trade-related threat or ecological threat).

4.2.6 Discussion

Designing a platform for transdisciplinary user groups of very distinct backgrounds implies the challenge of combining this different information that only scratches the surface and possibilities to dive deeper into the topic while remaining understandable and approachable for non-experts. For today's complex problems, however, a holistic understanding of interrelationships, including aspects not usually considered, is becoming increasingly important. Therefore, transdisciplinary projects involving domains that rarely cooperate hold high potential to identify comprehensive entry points for addressing these complex problems, as the following use case by instrument makers tries to emphasize and an additional second use case (see Subsection 4.2.8) on the variety of Malagasy Ebony by geographers underscoring the potential of *MusEcology*.

Use Case: Pau-brasil Bow Stick

For experts in musical instrument making and musicology, the initial focus and interest is on the orchestra and the search for details of groups of instruments - in this case, string instruments. As depicted in Figure 4.1, the separated listing of a string instrument bow as an own instrument and the relatively high number (210) of potential species used for making them, as well as the high ratio of trade-regulated species, is eye-catching and triggers the user to explore the details for string instrument bows further. Through the former selection, the Material View updates, and the user realizes that 170 materials are of plant origin and 40 are of animal origin. Hovering over the assessments of the listings in the timeline, one notes that the trade in whalebone, which was once used for the thumb leather to protect the handle of a bow, has been strictly regulated or even banned for all baleen whales since the late 1970s.

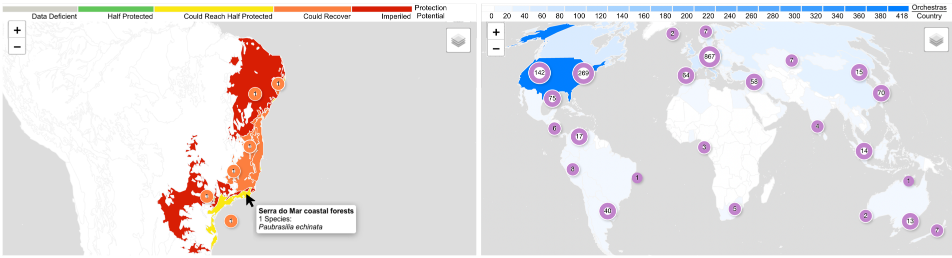

Figure 4.7: Left: Detailed view of the potentials for protecting half of the ecoregions with occurrences of *Paubrasilia echinata* showing in the tool-tip the category "could reach half" (yellow) for the ecoregion "Serra do Mar coastal forests" and its potential for protecting half. Right: World-wide distribution of symphony orchestras, shown by color-coded occurrences within country borders and purple "Threat" Donuts.

Scenario	**N**
Musical Instrument of Interest: Explore the 'Orchestra View' with its different instrument groups and the underlying musical instruments to find your musical instrument of interest and discover the musical instrument parts it consists of (**T2**). Observe the distribution of the used materials in the Diversity and Threat Map (**T3**) and their variety of appearances in the material view (**T4**). Switch between trade-related threat (**T5**), and ecological threat (**T7**) to observe the differences. Scan the timeline to find out about the history of these listings (**T8**). What is your impression regarding the current threat to your musical instrument (**T1**)?	16
Region of Interest: Explore the region you are most interested in and perceive the changes occurring in the other views when selecting (**T3**). Consider the different available scales (countries, ecoregions and hexagons as well as the protection potential (**T6**)) to find out more about the species richness and division of the threats. Switch between trade-related threat (**T5**) and ecological threat (**T7**) to observe the differences. What musical instrument groups require most species from the region of your interest (**T2**)? Which species are most threatened (Timeline View) (**T8**)?	12
Material of Interest: Explore the material view and focus on a visual appearance you are interested in (**T4**). Perceive the material clusters and discover the zoom levels offered down to the species level. Observe how the other views change according to your selections (**T2**). As a guide you can use what catches most of your attention or what taxonomic group you are most interested in. Find out about the geographical distribution of your selected material in the Map View (**T3**). How ecologically threatened or threatened by trade was the material over time (**T5,T7,T8**)? For which instruments is your material of interest used for (Orchestra View) (**T2**)?	8

Table 4.1: Visualizing this multidisciplinary, interwoven, complex topic shall support decision-making processes by providing an overview of all described aspects, their interconnections, and specific detailed information resulting in these domain-specific tasks. According to the questionnaire 81% of the participants felt satisfied (S5 rating ≥ 5) with the support by *MusEcology* in order to achieve the goals of their chosen scenario(s).

When switching over to the plant species of the Material View, the overview of ecological threats of species strengthens the impression that many materials face ecological difficulties and that the trade of these materials is possibly contributing to that situation. When selecting the stick as the essential component of a string instrument bow, it becomes apparent that most of these species come from Brazil, and not many come from other tropical regions/countries; only four European species are potentially used (see Figure 4.1). This triggers the user's interest to explore only potential Brazilian species on the map. The photographs in the Material View allow the user to recognize that wood appearance differs slightly between the used materials; this aspect by itself is interesting since the optical appearance of an instrument plays a vital role in its acceptance by musical instrument makers and musicians. Two species exhibit a decreasing population trend, and in 1998 - when monitoring population trends did not seem common yet, three species were listed as endangered. This suggests to expert users of the biology/ecology domain to consider the ecosystem's conservation state to place the information of the species in the overall context. However, scrolling down the species listed in the timeline, the users notice that only one species, *Paubrasilia echinata*, is listed in CITES and faces trade restrictions. With expert domain knowledge of musical instrument making or musicology, it turns out that *Paubrasilia echinata*, commonly known as pau-brasil, is the raw material high-quality string instrument bow sticks are primarily made of. This species is listed as endangered and since 2007 in CITES Appendix II. Zooming to that species and switching to the hexagon scale of the map, the user can get an impression of the range map with its occurrence mainly at the coast of Brazil in Figure 4.6, where the Material View also gives an impression of the wood appearance of *Paubrasilia echinata*. When reviewing the related ecoregions, experts from ecology and geography can confirm that the species only occurs in the *Mata Atlântica*, one of the 25 biodiversity hotspots worldwide. But non-domain experts can also get an idea of the ecoregions threat. Through the "Ecoregion Protection Potential" map layer, it can directly be identified that all ecoregions of pau-brasil occurrence are either in the category of "imperiled" or "could recover" indicating for the most significant part of the distribution area the severe situation of the species (see Figure 4.7).

Evaluation

Developing the different elements of *MusEcology* was a continuous process in the core team. At the same time, its applicability was regularly tested and evaluated by sharing key development steps with the Co-creation Team. We included a two-step approach for further improvements through external experts to expand this internal evaluation process. First, we shared the tool with three musical instrument makers and the Co-creation Team, who tested an intermediate pilot version, which entailed a further iteration to improve the platform. Considering the most urgent issues raised, we implemented fullscreen buttons to enlarge only one of the four main views to identify certain details; we recorded a video tutorial to introduce the concept and principal components of *MusEcology*, realigned and improved the switch between trade-related and ecological threats, and enabled the search for biomes and ecoregions. Already there, the experts highlighted the unconventional combination of information and innovative insights on interconnections, which for the first time clearly showed that the high number of plant and animal species used for musical instruments are distributed around the globe. For them, it became clear that this complementary cross-disciplinary information allows for a profound understanding of the complexity of the big picture and assists decision-makers at the local, national, and international levels. Great potential in the use of *MusEcology* was seen within instrument making schools, especially for young instrument makers who still need to build their wood stock - this would also imply knowledge dissemination and awareness building on that topic.

Questionnaires To evaluate and further improve *MusEcology* we set up an informal questionnaire study with 22 participating experts. The two videos of the supplemental material were shared as tutorial videos as an introduction to the tool and its functionalities. Next to basic questions (B1-B4) such as age, gender, background/profession, and level of expertise in additional domains, the questionnaires included five preference score questions (S1-S5) based on a 7-point Likert scale (ranging from *strongly disagree* (1) to *strongly agree* (7)) and three open questions (Q1-Q3). The test duration by the participants was, on average, 40 minutes. As guidance to explore the tool, we offered three scenarios, designed as different entrances and with the underlying domain-specific tasks (**T1**-**T8**) in mind (see Table 4.1). The participants came from the following domain backgrounds (B1): biology (8), instrument making (7), musicology (4), and ecology (3), whereby some participants stated strong additional knowledge (B2) in wood sciences, geography and the other already mentioned domains. 41% of the participants assigned themselves to female and 59% to male gender, whereby no one made use of the given further options (B3). 73% of the participants were between 20 and 39, 18% older than 60 years, and 9% between 40 and 59 years old (B4).

Usability and Support for Decision-Making The survey inquired quantitatively and qualitatively about the usability of *MusEcology*. 86.4% stated they learned something new (S1 rating of ≥ 4). The open question allowed us to identify the learnings (Q1) of the participants (% of participants that mentioned this learning), which can be categorized into seven aspects that form part of our tasks and confirm their successful completion, aligned by the twelve most liked features (Q2, see Figure 4.8). Additionally to their new learnings, 95.5% of the participants rated that the visualizations helped to understand the complexity of the underlying problem (S2) with a score ≥ 5.
Regarding possible improvements (Q3), three domain-specific desires were mentioned: Biologists in both evaluation steps pointed out that visualizing genuine/non-genuine changes in the timeline and considering multi-appendix and population listings in CITES would avoid misinterpretations. Wood science experts and enthusiasts desired access to macroscopic images, especially of the wood species. Musical instrument makers and musicologists needed to include common names for species and more explanations when hovering over acronyms, symbols, and icons. They desired additional mapping of further musical instruments and sustainable material proposals. In general, photographs or drawings of the plants and animals were mentioned to improve accessibility and support a better understanding, even for non-domain experts.

An important feedback from the participants was that 72.7% agreed or strongly agreed (≥ 5) that *MusEcology* supports decision-making processes towards more sustainable musical instruments and species conservation (S3). Although 31.81% wished for better performance on their devices (5 of them reported interface issues) and the intuitiveness (S4) of the system was evaluated with an average of 4.7 points. Overall, *MusEcology* fulfills the intention to unveil a perspective for

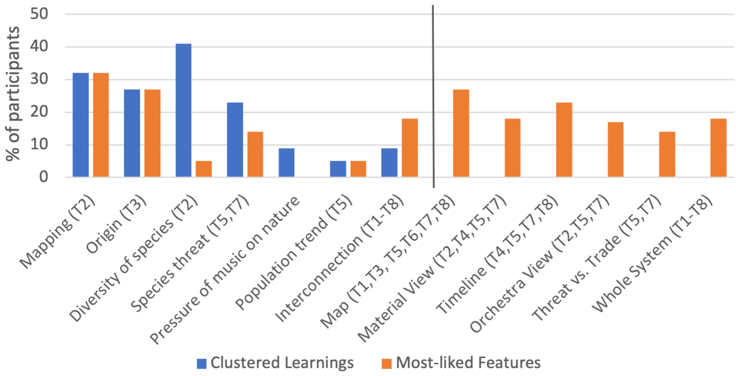

Figure 4.8: Clustered overview of learnings thanks to using *MusEcology* by questionnaire participants in blue on the left side. On the right side, explicit mentions highlight the clustered and most-liked features in orange.

sustainability in musical instrument making, simultaneously serving for awareness building and enriching different research fields.

Limitations and Future Work

Some limitations exist in data availability, such that we only had access to 388 distribution maps of 758 species used for musical instruments. Similarly, the selection of photos of the individual materials thus far is still limited to 209 of the different species. Another major limitation is data inaccuracy of information assigning instrument parts to specific materials. The designation in craft and trade is mainly based only on common names; therefore, possibly fewer species than presented here will be used in musical instrument making. This is especially the case for the species of the genera *Diospyros* (ebony) and *Dalbergia* (palisander/rosewood). Many potentially used ebony and rosewood species, as well as their visual similarity, in particular, regarding the ebony species, is also part of the reason for many missing photographs of these wood species. As already mentioned in the evaluation of the platform, possible misleading interpretations of data also represent a limitation. For example, the threat listings in the timeline do not indicate whether a change in the listing category was genuine or non-genuine. Thus, a change in the threat category does not necessarily imply a trend. Threat causes are another piece of information that users might speculate on, though not indicated in the platform. As part of a user-friendly design for casual users, we plan to include summed-up information per instrument as "cards", allowing them to quickly grasp the most important findings by small multiples. In addition we have already used our visual design as part of an interactive visualization-based storytelling to reveal and disseminate the intangible cultural interlinkages [253], with more examples to follow in the future. Remarkable future developments would be the extension of ecological contextualization by including aspects of species threat at the level of ecosystems, e.g., occurrences of species in biodiversity hotspots. Projections regarding the potential effects of climate change, forest losses, and land-use changes in different ecoregions would enable the expert to give rough interpretations of future pressures on species used for musical instruments. Including physical and acoustical material characteristics would allow guidance regarding alternative materials. In sum, this would enable a more comprehensive consideration of long-term aspects relevant to the sustainability of musical instrument making.

So far, our focus on musical instruments of the world is limited to classical musical instruments visually clustered in a symphony orchestra as a symbol for classical music. However, we intend to extend our approach that links musical instruments with the materials these are made of to other music cultures. Examples in literature for those relations are traditional pan flutes found in the Andes of Bolivia analyzed by Hachmeyer [158], as well as the traditional musical instruments located in the Brazilian Pantanal - the viola de cocho, ganzá, mocho and tamboril - as focused on by Kölble [239]. A database approach mainly focused on non-classical musical instruments and materials was chosen by Brémaud, Thibaut, and Minato [51], although it did not link the materials to the ecosystems they originate from.

This design study contributes by opening a novel perspective on thematic approaches that would highly profit if picked up for future visualizations. For cultural traditions and arts, the reveal of the origin of used materials could be transferred to different contexts, e.g., natural materials for theater scenes or color pigments for fine art. Potentials for visualizations again are the invisible aspects of supply chains, such as "virtual resource consumption", e.g., the water used to produce jeans. Including fossil resources would also open a completely different need, e.g., for plastics or metals, visualizations regarding the various alloys and linking them as all fossil resources to global raw material deposits. Accordingly, environmental destruction, pollution, and their effects on society open further creativity fields for visualization design. Another contribution is the transferability to develop new thematic and representative schematic visualizations. Effective and understandable visualization elements can be created by involving multidisciplinary perspectives, such as the hierarchically structured Orchestra or Material View, enhancing statistical evaluations by domain-specific icons or multi-media elements.

4.2.7 Conclusion

Interconnected "global orchestra ecosystems" are threatened by various social and natural challenges such as climate change, biodiversity, and habitat loss and require sustainable future pathways originating from distinct domains. By bringing together domain experts from ecology, biology, geography, musicology, instrument making, and computer science, we developed *MusEcology* as a platform to support sustainable environmental decisions. We combined various aspects relevant to the sustainability of orchestras with the materials used for musical instruments from the meta-level via the macro level to the micro level regarding species richness, trade-related and ecological threat in time and space, and the hierarchical taxonomic differentiation related to the material appearance. With this combination, *MusEcology* is the first visualization platform of a complex global cultural-ecological system that links academic with traditional knowledge systems considering space and time. The four interactive, multi-level views invite the user to immerse in the details of the materials used for the musical instruments of a symphony orchestra. Pursuing from these details, this platform does not provide specific solutions for more sustainable musical instruments and orchestras; moreover, it shows that an orchestra ecosystem might require a multifaceted solution pathway. Existing approaches, for example, regarding material diversification and alternative materials based on physical and acoustic characteristics, need to include essential aspects for sustainability in a holistic understanding. Instead, such approaches need to consider the shown interrelations and consequences from perspectives of different domains to satisfy the complex requirements. Cultural-ecological sustainability could consider approaches such as sustainable harvest, socially fair trade - documented transparently along the entire supply chain - or solution approaches that might affect or contribute to the loss of cultural traditional knowledge (e.g., new non-natural/artificial materials or modified materials). To identify protection priorities from an orchestra ecosystem's perspective, biodiversity hotspots offer a starting point for further interdisciplinary research to direct conservation activities to preserve the ecosystems an orchestra depends on. We plan to further enhance this platform of a global cultural-ecological system of a symphony orchestra in the manner described above as a base for more sustainability of musical instruments to raise awareness of and contribute to a balanced and harmonious interplay of nature and culture.

Acknowledgments

We wish to thank Prof. Gerald Koch and Dr. Volker Haag of the Thünen-Institut Hamburg for providing photographs of the extraordinary Mautz-Collections. We would also like to thank Emily Beech and Dr. Malin Rivers from Botanic Gardens Conservation International (BGCI) for sharing their expertise and their ongoing assistance regarding tree assessment data and representation of it. This work was supported in part by a grant from the Heinrich-Böll-Stiftung.

4.2.8 Appendix: Use Case – The Variety of Malagasy Ebony

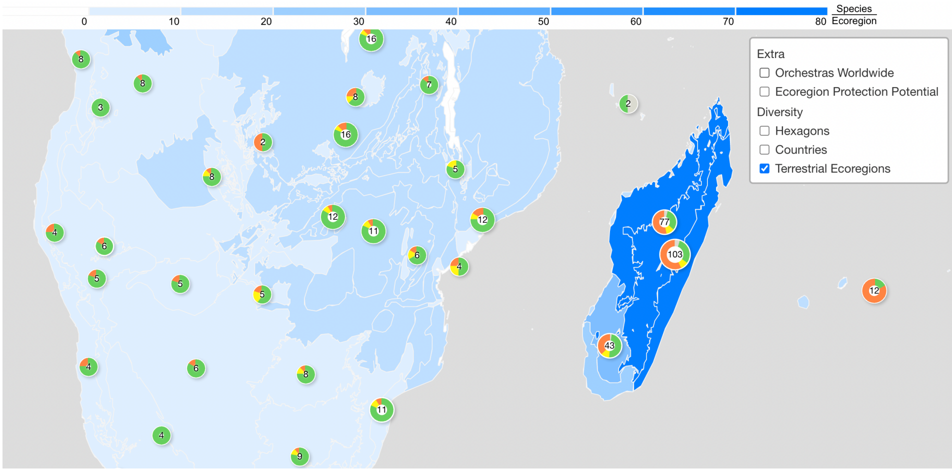

Figure 4.9: Ecoregions of Madagascar showing that lower species richness for musical instruments (light blue) can be found in the dry southwest than in the northern ecoregions of Madagascar (darker blue), with 103 and 77 (numbers indicated in the threat donuts) species potentially used for making musical instruments. The legend shows that the blue tones in each ecoregion represent the number of species per ecoregion. A lighter blue represents fewer species per ecoregion than darker blue.

A first glance at the overview of the world diversity map shows that Madagascar stands out in the species richness that may be used for musical instruments. The Threat Donuts belonging to Madagascar show that a strikingly high percentage of species are threatened or trade-restricted. That leads the user to take a closer look at Madagascar; clicking and zooming to the country automatically selects the species only occurring in Madagascar. The high number of plant species presented in the Material View triggers interest in selecting them for a closer look. At the first zoom level, the Material View shows that most species from Madagascar belong to only two families *Fabaceae* and *Ebenaceae*. When navigating the two families individually in the Material View, the dominant genera *Dalbergia* and *Diospyros* pop up. In respect to the wood appearances in the Material View, domain experts from the wood sciences know that the Latin genus *Dalbergia* is commonly named palisander or rosewood and in the case of *Diospyros* as ebony. Acknowledging the extraordinarily high species richness of *Diospyros* and *Dalbergia* in Madagascar and shifting the focus to the orchestra view allows us to recognize that both genera may be used for instruments of all instrument groups of an orchestra, apart from the brasses. Specifically, there are 46 palisander or rosewood species, and 45 are endemic to Madagascar, which means they only occur there. Besides, there appear 91 ebony species, of which 89 are endemic to Madagascar. In a close reading through the timeline, it becomes evident for the user that in 2017 (see Figure 4.10), a decision for trade regulations must have been made that encompassed the whole genus of both *Dalbergia* and *Diospyros* and many species threat assessments by the IUCN Red List had been conducted between 2019 and 2021. Additionally, ecology or geography domain experts may complement that Madagascar is one of the 25 global biodiversity hotspots having an extraordinarily high number of endemic species occurring only on that island; this adds weight to the number of threatened species that are used for musical instruments (see Figure 4.9). The differentiation in ecoregions shows that most species occur in forest landscapes and less in the dryer south of the island. In the hexagon perspective, considering the distribution of the species, it becomes evident that less species richness for musical instruments occurs in the southwest of Madagascar, while the highest species richness is found in the northeast.

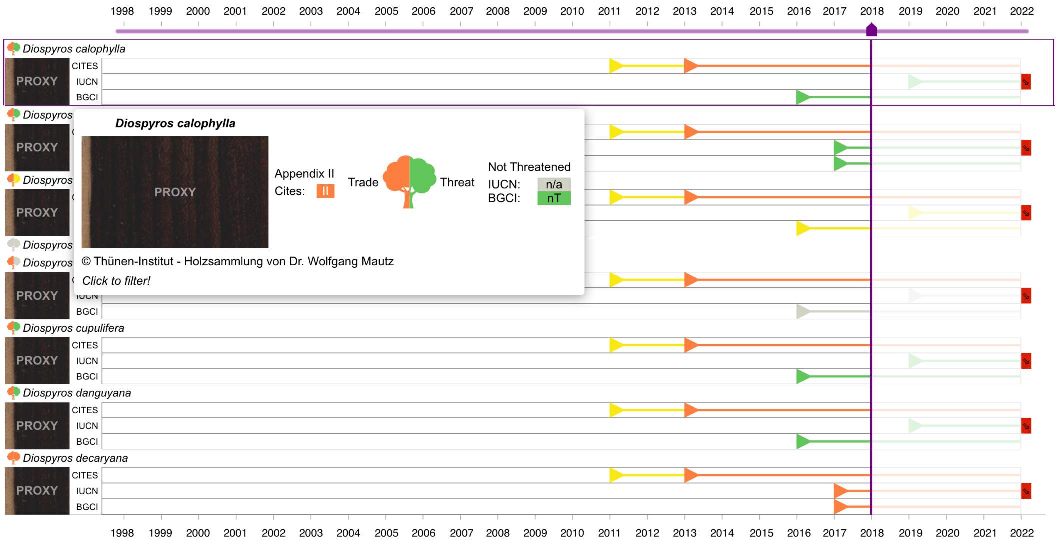

Figure 4.10: The timeslider assists the user in identifying that, for instance, in 2017, *Diospyros* was listed in CITES for trade regulations which affected the entire genus since the summarizing threat icon refers to the latest assessments in the focused time frame 1998 – 2018.

4.3 Paper 5: Visualization-based Scrollytelling of Coupled Threats for Biodiversity, Species and Music Cultures

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Abstract: *Biodiversity loss, land use change and international trade are the main causes for an increasing number of endangered species. As a consequence resource scarcity due to endangered species also threatens cultural heritage. To depict such coupled threats and their interconnections for the specific case of musical instruments of a symphony orchestra, the MusEcology project developed a platform to analyze dependencies between musical instrument manufacturing for symphony orchestras, and threat assessments to plant and animal species used as resources. Non-experts are rarely aware of this intertwined threat. Therefore, low-threshold information distribution is urgently needed. We extended the MusEcology platform with scrollytelling functionalities helping domain experts drafting stories that use the visualizations of different dimensions throughout various zoom levels. We outline the utility of our approach with a particular scrollytelling example of the threatened pau-brasil wood (Paubrasilia echinata (Lam.) Gagnon, H.C.Lima & G.P.Lewis), endemic to the Brazilian Mata Atlântica, ever since 1800 used for sticks of high-quality string instrument bows. The story of the natural material from forests to instrument-making workshops, musicians and audiences is told through informative texts, interviews, sound recordings, photographs, and schematic drawings. By bringing together expertise from different fields, this story highlights the interconnected dependencies between ecosystems, culture, and music. The interactive storytelling experiences are aimed at casual users and policy makers to raise awareness of the underlying complexity of biodiversity and instrument making, to support related and induce necessary decision making processes, and to unfold possible pathways towards a more harmonic and sustainable music ecosystem.*

4.3.1 Introduction

Biodiversity loss is one of the biggest threats to our natural world. According to the Red List of endangered species of the International Union for Conservation of Nature (IUCN), worldwide more than 42,100 species are threatened with extinction, which corresponds to 28% of all assessed species [419]. Threatened species worldwide form part of many different ecosystems and ecoregions also increasingly threatened by degradation and/or land use change. Many threatened species are important for cultural traditions and cultural objects, and provide important cultural and provisioning ecosystem services. Alone for the construction of orchestral musical instruments potentially 761 species may be used, according to the IUCN Red List about one third of them are threatened by extinction ([254] in submission). A symphony orchestra is composed of groups of musical instruments, each consisting of different instrument components made from various materials, similar to an ecosystem composed of its different organisms—an orchestra ecosystem.
The interconnection of species used for cultural objects to the objects themselves is rarely analyzed simultaneously as contextualized by Lichtenberg et al. [269] in a theoretical framework of cultural-ecological systems. Kusnick et al. ([254] in submission) developed *MusEcology* that provides in-

terconnected contextual-environmental information about species distribution, species threats and their trade regulations on country, biome, ecoregion and range map level to a symphony orchestra with its musical instruments in a visual analytics system designed for domain experts. The fragile cultural-ecological relation is threatened by trade and the complex global problems which is indicated by the fact that many species are already listed as threatened and trade-regulated. The preservation of the culture and endangered species should therefore be a declared goal and requires the cooperation of various experts in order to illuminate the complex connections from different directions. However, the continuously worsening situation regarding biodiversity and species loss calls for raising awareness that culture depends on nature with its intact ecosystems.
To reach the above mentioned aim, we extended *MusEcology* by storytelling—considered as "the soul of science communication" [211]—to make complex information about threats to biodiversity, species and culture intuitively accessible and comprehensible to a non-expert audience. The leading example throughout the paper will be the bow of string instruments, an ideal case to describe these interconnections, because many materials of the different bow parts originate from endangered species. The most important part of a bow is the bow stick and best suited as an example for a storytelling feature with the aim for an increased accessibility of our collected data and knowledge from *MusEcology* for target groups like instrument makers, musicians and interested public. The sticks of high-quality string instrument bows are exclusively made of pau-brasil (*Paubrasilia echinata*), Brazilians national tree, that is endangered and endemic to the Atlantic Forest, its wood has a unique set of characteristics relevant for string instrument bows [269].
Ultimately, our approach aims to give a better understanding of the complexity and huge geographical distances between the telecoupled systems by zooming and panning throughout a geospatial map central to the scrollytelling experience. We evaluated the utility of our approach in an informal user study, and gained confidence that it can play an important role to enhance decision making processes and to encourage initiatives for biodiversity conservation linked to species-specific preservation and restoration to preserve culture.

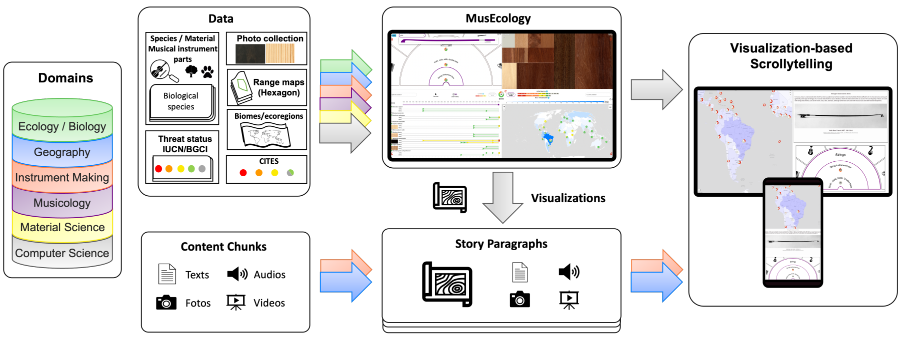

Figure 4.11: Overview of the diverse data repositories linked to our six key domains: ecology/biology (green), geography (blue), musical instrument making (orange), musicology (purple), material/wood sciences (yellow), computer science (gray) and their merged processing towards the four different interconnected views: Orchestra, Material, Threat Assessment Timeline, and Diversity Map of *MusEcology* and the enhancement by the stories' paragraphs which incorporate the visualizations, and content chunks.

4.3.2 Background

The scrollytelling draws on the *MusEcology* platform ([254] in submission). It allows an interactive exploration on different levels in regard to the diversity, distribution and threat of species potentially used for musical instruments of a symphony orchestra. The storytelling feature accesses data sources of *MusEcology*, such as the map of orchestras worldwide, the distribution maps of species used for musical instruments of an orchestra, the databases of the IUCN Red List, Speciesplus of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) [74] and the Botanical Gardens Conservation International (BGCI) GlobalTreeSearch [42] and ThreatSearch [41].

The story of string instrument bows picks one example of a musical instrument part of utmost importance, the bow stick, that depends on a highly threatened species, pau-brasil (*Paubrasilia echinata*), to combine the interactive information provided by the platform with selected scientific findings on pau-brasil to contextualize the controversial situation of natural and cultural threats. The variety of research findings about pau-brasil cover a wide range of aspects regarding this species that is relevant for the Brazilian local culture and for the classical music culture, more precisely for the sticks of string instrument bows and for the species itself. Few of these scientific findings are accessible and communicated in a way that allows comprehensive understanding for non-scientific, interested, and/or affected actors (e.g., bow makers, musicians, Brazilian population, violin makers, etc.). By bringing expertise of researchers with different disciplinary backgrounds (geographer and computer scientists) together with domain perspectives of violin makers this story gives insight into the tense situation of pau-brasil, following the way of the natural material from orchestras, via forests and instrument making workshops, back to the audience of concerts, highlighting the interconnected dependencies and interferences. Traditionally these information are gained by field trips, interviews and literature reviews and communicated for example by static maps or timelines. The bundled expertise of the team that developed the *MusEcology* platform draws on computational power to mass process, fuse data, and visualize the combined dimensions throughout various zoom levels or via juxtaposition resulting in an interactive data-driven storytelling, raising the awareness of the inter-connection and showing possible pathways towards a more harmonic orchestra ecosystem. We visualize different levels of detail in the map, where the distribution and diversity of species is shown in levels of countries, ecoregions and within an artificial hexagon grid. The ecological and trade-related threat assessments to the species are supplemented via summarizing icons and donut charts, whereby the histories of them are made clear by timelines. To convey the story, we move along these detailed levels through space and time to contextualize information with historical developments and their consequences regarding the story of the string instrument bow via scrollytelling. However, the narrative is told through informative texts and translated interviews with Brazilians and experts, accompanied by their original sound recordings, photographs and schematic drawings highlighting technical details and the interconnection of the manifold details from various domain perspectives.

4.3.3 Related Work

Geospatial Views. To represent particular values, such as the population density of a certain species, in specific areas Choropleth maps are commonly used [96, 195, 309]. The use of hexagonal tiling is preferred when an artificial grid is utilized to divide individual areas [298]. Also visualizations for global forest loss [440] or the habitats of selected species can be presented geographically through the use of geospatial heat maps [148, 205, 417, 421]. Glyph-based maps can be designed to communicate various aspects of fruit tree species distributions, as demonstrated in Albania [145]. Additionally, the distribution of tree species in a limited spatial area can be displayed effectively using tag maps, which show the most common species in an aggregated spatial area [355, 372].

Temporal Views. Time-based visual depictions of species tell stories like the life cycle of the Japanese beetle [428] or overviews of the evolution of dinosaur species [174] and a timeline-metaphor is telling stories of musical instruments and their matched musical compositions [252].

Visualization-based Storytelling. Since centuries stories are told to communicate information in an understandable and memorable way, and are just as long depicted by for example rock wall paintings [38]. Through the ongoing digitization and visualization nowadays the topic remains of high interest and creates value in a broad variety of economy branches and research fields. Storytelling is considered as "soul of science communication" [211], increasing comprehensibility and involvement of recipients, especially by interactions [281]. Sequences of changing circumstances of characters throughout the story thread create in their unique combination a comprehensive storyline [281, 427]. These episodes are often told with the support of temporal and geospatial views. General discourses and surveys on visual storytelling [242, 296, 405, 427] analyze and categorize visualization techniques for scientific stories or journalistic data stories [391]. Kusnick et al. report on narrative visualization techniques for person and object data on cultural heritage [247] and focus on "visualization-based" storytelling. They review music culture-related stories on teacher-student and album-instrument relations within network graphs and data-comics [197, 227], and also encounter environmental stories on micro-climate within the streets of Vienna, Austria via mixed reality. The affirmation of the use of storytelling as an memorable outreach for such data is originating from the ongoing research and development of comprehensive multimodal systems regarding cultural heritage object and person data such as "InTaVia" [291]. Storytelling also gains importance in the communication of insights from the environmental science especially for specific target audiences such as on world heritage and biodiversity for children [118, 369] or people older than 55 [328].

Scrollytelling. One of the common visualization-based storytelling implementations such as "annotated chart", "data comic" or "slide show" is called "scrollytelling" where the main interaction is implemented through scrolling. This technique is often used by online articles in combination with illustrative videos or three-dimensional renderings such as the fire outbreak at the Notre-Dame cathedral published by New York Times [322]. Scrollytelling that incorporates maps as a central part and the locations to which certain information can be connected is widely used, e.g., in a recent newspaper regarding illegal logging and the timber mafia [407]. Photographs are also widely used, especially in connection to cultural objects [343]. In summary, none of the related works supports the visual analysis of the interrelation of endangered species and the interconnected threat of natural and cultural heritage across continents.

4.3.4 Methodology & Visual Design

This visualization-based scrollytelling resulted from a participatory visualization design process [203] within our core team of two computer scientists together with a geographer, who also is a violin maker, in a design by immersion approach [159]. Additionally, our decisions are based

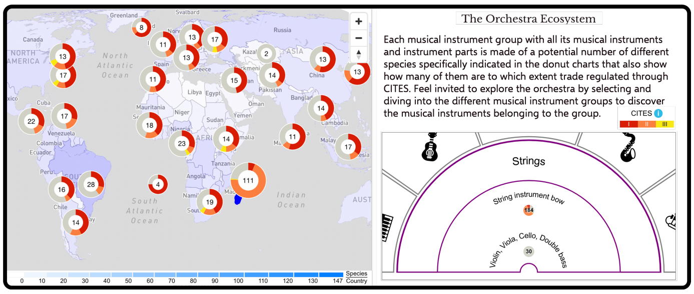

Figure 4.12: On the left side the map is showing the materials/species used for string instrument bows and their trade regulations in the threat donuts. On the right side a schematic orchestra is shown zoomed in the string instrument group that consists of violins, violas, cellos and double basses. All instruments consist of different musical instrument parts. In its connection to the species the instruments are made of and under consideration of the orchestra functioning this is can be called an orchestra ecosystem.

Figure 4.13: Left: Map with hexagons showing the distribution of pau-brasil along the Brazilian coast within the Atlantic Forest (Mata Atlântica - in yellow). The map is switched to a satellite view automatically to reveal insights into topology and vegetation. Right: Explanations to the pau-brasil tree and photographs of its unique flowers and bark.

on findings of the long-lasting collaboration with a co-creation team (two computer scientists, one ecologist, one geographer, two biologists) and external domain experts from the creation of *MusEcology* (see Figure 5.15). Cultural actors, objects and groups of them (e.g. orchestras) are traveling around the world and so do the resources used for culture, whereby the involved craft traditions represent an intangible cultural heritage on their own as well. *MusEcology* tries to inform about these aspects by focusing on globally consistent information details, but it lacks all the (intangible) information and the socio-cultural meanings hidden in the stories all around. Especially music is touching, often very personal and almost everyone has a connection to it. But these complex and rather intangible details and side-stories remain hidden and are waiting to be told and put into context. The interactive storytelling added to *MusEcology* tries to encounter this and is meant to create an additional specificity for the creation and perception of memorable and immersive stories on the diversity, distribution, threat of natural species used for the production of musical instruments and the distances between the interlinked levels and multi-modal (story)

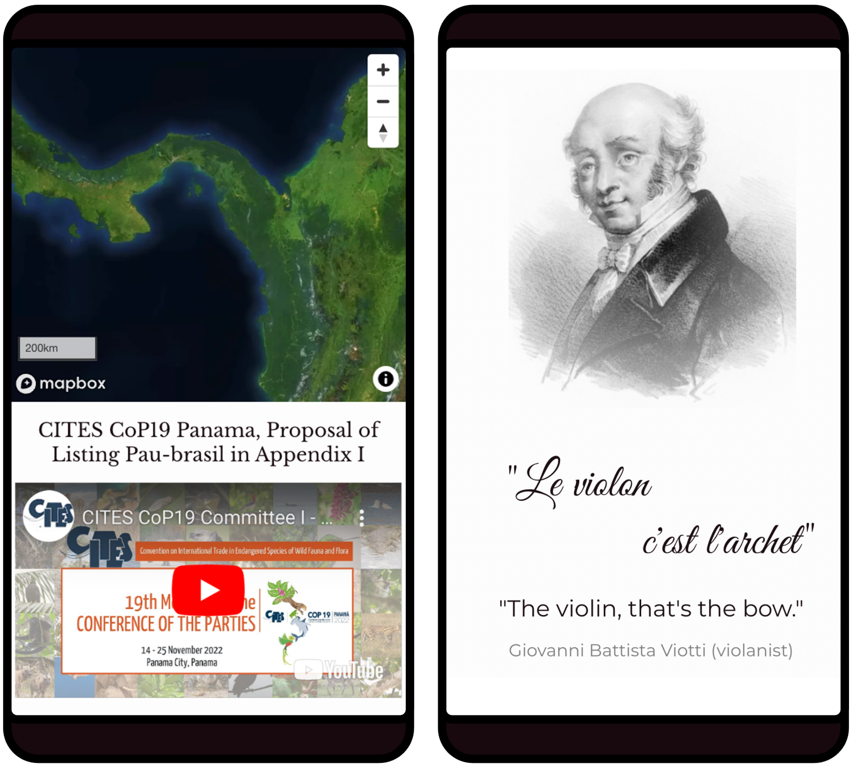

Figure 4.14: Left: Responsive mobile portrait view with stacked map and content area including a video, documenting the CITES CoP19 in Panama [70]. Right: Fullscreen quote by violinist Giovanni Batista Viotti [453] to emphasize the importance of string instrument bows.

characters of touched systems. Therefore, we decided for the geospatial map as main visualization on the left side of the equal divided screen. To minimize the distraction and keep the orientation we decided for a static two column layout where the right screen half is a scrollable content area to tell the story by a variety of content chunks (see Figure 4.12). As a first story we choose to implement the "Story of the String Instrument Bow" because we wanted to approach the complex topic from the symphony orchestra as entry point and since the bow stick is made from the endangered pau-brasil, it is currently facing controversial discussions. The driving interaction throughout the story thread is scrolling, as it allows for direct, responsive, and bidirectional control and is widely used on social media and mobile apps [311]. By the reach of story paragraphs within the focus area of the content half on the right side, the map view on the left is "flying" to a given position and zoom-level by smooth transitions of zooming and panning. Just as in MusEology, we used *JavaScript* libraries such as *React* and *D3.js* to create our web app and visualizations, but for the maps we used *Mapbox GL JS*, because it allows for useful projections (e.g. 3D globe) and "fly-to" animations.

Map & Layers

Already *MusEcology* has a map that includes a variety of "map modes" defining which information is visualized by which polygons and clustered glyphs within each mode. The map offers seamless switches between these modes, "fly-to"-transitions and zoom ranges from overview of the whole world to single buildings. Each map mode consists of three layers: (1) base map (e.g. light, dark, satellite), (2) polygons (countries, ecoregions, artificial hexagon grid), and (3) additional statistical and clustered glyphs (e.g. threat donuts, orchestra clusters) on top of them. Thereby the amount per entities within the polygons is depicted by a blue shaded heatmap. In case of the country mode these entities are either the various species used as resources for musical instruments or orchestras worldwide. On top of the countries capitals are "Threat Donuts" symbolizing either the overview of trade regulations by CITES or the assessed ecological species threat that is provided by IUCN and BGCI by colored circle segments (see Figure 4.12). In case of switching the map mode to ecoregions and hexagons the entities remain the species as heatmap and the threat markers are placed on the surrounding ecoregion's center point. The map modes can be easily changed by the activation of the according content chunks and the interactive legends are explaining the visual elements and allow for details-on-demand through filtering and hovering. During our example story on *Paubrasilia echinata* we are progressing from an global perspective on symphonic orchestras over trade regulations in Brazil, focusing on the ecoregions close to the coast, towards the reveal of pau-brasil's distribution as hexagons (see Figure 4.13). To minimize the distortion of areas, we chose the equal area projection by *Mapbox*.

Content Chunks

To tell and illustrate the story we offer a variety of multi-media "Content Chunks" as building blocks consisting of textual, medial and interactive visualizations as seen in Figure 5.15. They can be used, customized, and combined to craft an author-driven story within a JavaScript Object Notation (JSON) stating all the different stations and appearances throughout the story in a list of "Story Paragraphs".

Texts & Quotes. The easiest way to convey a story is by narrative text. Therefore we offer a selection of harmonizing font-family pairs for headlines and text contents. Special cases for texts are width filling Titles, Quotes, End Cards with further information such as subtitle, translation and authors. Worth to mention is that all the textual content definitions are able to handle HTML as markup language to customize the contents even more. An embedding of e.g. tables is becoming possible by it as well. This can also be used to reformat text so that it becomes e.g. a transcript of an interviewing dialog of story characters.

Images. To illustrate stories, multi-media data is broadly used in storytelling approaches. Therefore we allow to embed single and/or multiple online available images as galleries by the statement of link urls. More explanatory context is given by the images through their optional captions and copyright statements.

Videos & Audios. Similar to the images the data is defined by link urls to the used media source and optional captions, and copyright information. By indicating the starting time in seconds, the story editor can skip unwanted parts of available contents such as an intro of audios or videos. Since embedded media files allow to be automatically played on websites, they can be used to convey the story, or increase the atmosphere and immersion by enhancing video material, insightful interviews or background sound effects. But because automatically starting media can be potentially disturbing, this functionality remains an opt-in at the beginning of the story, while the recipient remains in control of the playback by the visual interface.

Visualizations. Building on top of the system architecture of four juxtaposed but linked visualizations of *MusEcology*, the story also allows to make use of the already implemented visualizations and visual glyphs. Thereby, the visualizations stay linked to the map, so that interactions within one content visualization on the right could alter the appearance of the map to the left. This fact can be used to create breaks within the linear story flow and allows for higher degrees of freedom for the recipients. The case of the nested orchestra view enables on demand an exploratory analysis of distributions and threats of species used for the various musical instrument groups and their containing instruments as shown in Figure 4.12. Similar to this, the Timeline View can create insights into the history of trade-related and ecological threat assessments of selected species. All these building blocks can be combined, allowing the creation of rather complex stations within the story.

Interactions

The inter-linkage between story paragraphs and map is given by an annotation of the story contents with a desired map base-layer, map modes and specific geolocations to fly-to when the story paragraph is scrolled into the focus area. Additional filter for the data shown in the selected map layer such as “Filter for only hexagons of *Paubrasilia echinata*” allow the focus on its rather limited distribution with the option to switch to a satellite map-base, revealing a first impression of the vegetative circumstances in that area. This mechanic also drives the interplay between the additional visualizations and story map, such as the Orchestra View applies filter for species used for user-selected musical instruments and instrument groups. Furthermore, the activation of story paragraphs by scrolling enables for rather artistically effects e.g. the change of background color as used in the orchestra hall to simulate the dimmed lights for the audience. During the development we considered a responsive design of our visualizations and Story Paragraphs, so that the story can also be presented on mobile devices in portrait-mode, whereby the map view is positioned above the scrollable content area, as depicted on the left side of Figure 4.14.

4.3.5 Informal Evaluation

We conducted an informal evaluation in order to investigate if our approach suits to educate casual users on the interconnections between biodiversity and instrument making, using the implemented story on the string instrument bow stick, whereby the participants received no training and no information on the story’s theme.

Participants. The setup as an online evaluation helped us to reach a good number of interested participants for feedback on our first prototype. We invited people with different backgrounds to gain a heterogeneous group. We received 19 responses from participants of different age groups (see Figure 4.15) having diverse professional backgrounds. We ensured that none of the participants had a background in biology and musicology.

Scrollytelling Experience. We wanted to know from participants how well the scrollytelling supported to learn about the underlying concept. On a 7-point Likert scale from *strongly disagree* (1) to *strongly agree* (7), we firstly asked them how intuitive the scrollytelling was. With an

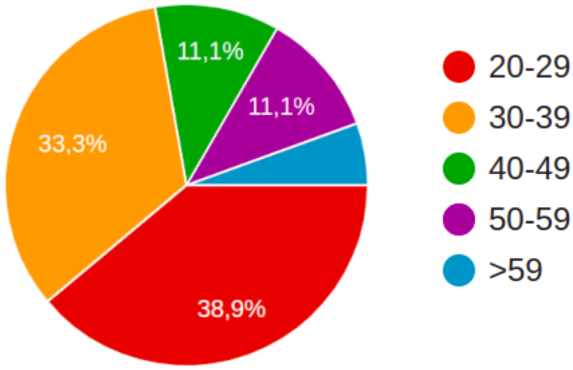

Figure 4.15: Age distribution of the participants.

average of 5.4, the majority of participants found the approach rather intuitive, only two participants found the bow stick story counterintuitive (see Figure 4.16). We secondly asked on how valuable the visualizations were to understand the concept and to facilitate the learning experience. Although a majority of eleven out of 19 participants were on the positive side, the answers were mixed with an average of 4.7 (see Figure 4.17). One reason would be that next to the visualizations diverse contents like rich media were used to tell the story, which may lower the perceived importance of the visualizations used. However, users who gave a lower score for intuitiveness also tended to give a lower score when rating the importance of the visualizations.

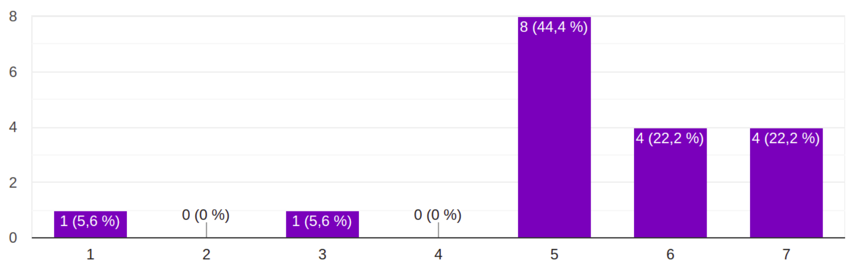

Figure 4.16: Intuitiveness of the scrollytelling approach.

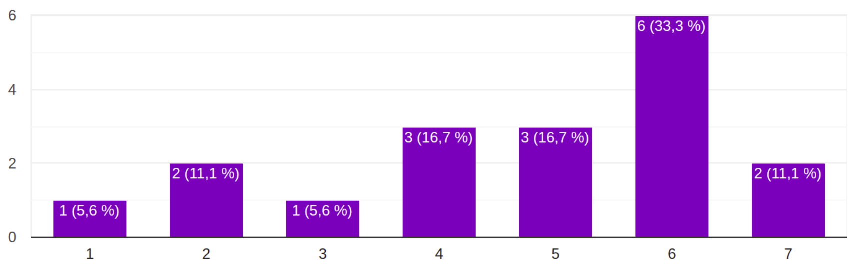

Figure 4.17: Importance of visualizations in the scrollytelling.

Learning Effect. With an average of 5.8 on a 7-point Likert scale from *strongly disagree* (1) to *strongly agree* (7), nearly all users confirmed to have learned something new through the scrol-

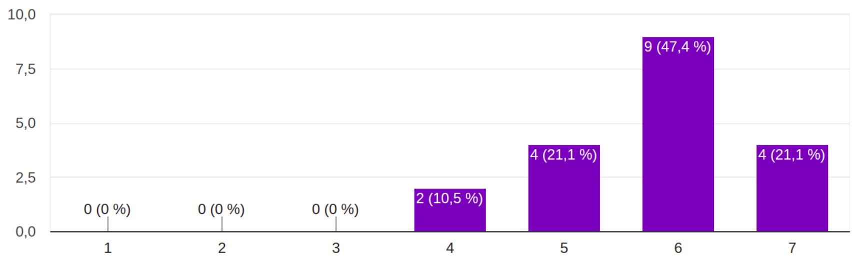

Figure 4.18: Learning effect through the scrollytelling.

lytelling. We asked them what they had learned. 13 of 19 participants directly replied that they were not really aware of the threats to the natural resources musical instruments are made of (see Figure 4.18). One of the replies was exactly what we wanted participants to learn: *"History about something I had no idea about - and never really thought about before."* Other participants mentioned they learned about illegal trades, the composition of orchestras or the scrollytelling technique itself.

General Feedback. Nearly all participants gave constructive feedback and suggested improvements, which we consider an indicator for user engagement. While we received some comments on how to improve the structuring of the story itself, participants also suggested to improve the technological features of the scrollytelling approach. While some of these were due to the circumstance that we used the first story draft during the evaluation, other suggestions made us aware of obstacles for users during the scrollytelling experience. Overall, the feedback can be turned into general recommendations:

- The story must be carefully introduced at the beginning.
- The relation between visualization and content has to be clear.
- Visualization and content need to be balanced.
- There has to be a red thread between two subsequent story items.
- Using rich media like sound and video enhances the experience.

4.3.6 Discussion and Limitations

The main strength of digital storytelling in general as well as in our case is mixing fact based information with multi-media impressions and personal stories delivered through interviews to address emotions and foster connection and identification with the story [296]. Part of our outreach intention is to break down expert knowledge often collected by single researchers into understandable and memorable facts communicated by memorable narrations. For captivating storytelling of such expert knowledge user-adapted text formulations and a good story flow are key elements [427]. This process of storytelling alone requires a lot of knowledge and effort, but to depict the story by interactive visualizations the domain-experts also need to have (technical) understandings of visualizations. Therefore, data-driven story creators and storyboarding tools should support the editor to craft narrative visualizations [227, 247, 311], but often lack the possibility to use already customized visualizations, such as the artificial hexagon grid and the ecoregions with threat levels of the *MusEcology* platform. Moreover, as a challenge and finding within our interdisciplinary collaboration, we figured out that domain experts often prefer to continue their research and storytelling elaboration within tools they already know. This is why our approach so far relies on the collaborative conversion of stories drafted in slide shows and spreadsheets by the domain-experts into the JSON-configuration of story paragraphs and their contents with the help of computer scientists. To overcome this limitation one avenue for future work could be to include a story editor interface or the possibility to make *MusEcology* and its elements available though e.g. url parameters to use them in stories crafted in external tools. Even though small visual elements like the interactive color legend might be difficult to integrate into other editor tools. We opted for a linear story design with specific use cases because the entire system might be too complex and overwhelming for a broader public audience, not used to exploratory visualization approaches. Nonetheless, all of the interactive visualizations can be used within the stories as interactive breaks within the story flow and function also as starting point for exploration and future stories on instruments, regions, materials, and species. Therefore, our scrollytelling allows to reach casual users and to draw their attention also beyond the specific case to the general problem of an increasing number of threatened species due to its connection to the existing *MusEcology* platform. The connection between music cultures, their musical instruments and threatened species, specifically the string instrument bow and the threatened pau-brasil tree, brings environmental concerns together with cultural values. This allows casual users that have a relationship either to the cultural value or to nature to personally relate to the described cultural-ecological threat. Current global environmental challenges, such as biodiversity loss and species extinction require linking such large, hard to grasp topics to the personal level to trigger careful decision making processes as well as biodiversity and species conservation activities. Our visuals and system are based on the data and visualizations already available in *MusEcology*, and are therefore able to provide scalability and generalizability as the platform was developed with a global and multi-zoom-level approach in mind. However, remaining challenges are the ambiguity of (common) trade names. The lack of scientific explorations or limited or insufficient scientific findings for some musical instruments and their species complicate the creation of stories for each musical instrument. Albeit these challenges domain experts currently develop stories about other musical instruments and their parts being resourced from fragile ecosystems, e.g., African blackwood (*Dalbergia melanoxylon*) that is used for clarinets and oboes, or the vulnerable Bahia rosewood (*Dalbergia nigra*) being the most valued material for high-end guitars.

4.3.7 Conclusion and Future Work

We developed an interactive digital scrollytelling to narrate complex interconnection of cultural and natural heritage across large geographical distances. The first story example drafted about the string instrument bow not only addresses the main goal and succeeds to raise awareness for this intertwined challenge of species threat and the threat for the tradition of bow making, it in particular highlights the potential of a more user-friendly introduction for casual users to complex data sets offered through the *MusEcology* platform. Our approach gives the domain experts the opportunity to tell these stories using complex data for the first time.

Future developments of our storytelling interface include a deeper zoom level on the specific protected areas with occurences of target species' to more impressively demonstrate how rare species like pau-brasil are nowadays. We will further adopt several narration techniques provided by the InTaVia storytelling suite [291] that are suitable for the *MusEcology* project, such as facilitating user engagement with gamification elements [178] like small riddle questions or quiz elements, or reshaping the story arc by choosing different story entry points.

Acknowledgments

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5 Universal Approaches to Visualization-based Storytelling

"Technological progress has merely provided us with more efficient means for going backwards."
– Aldous Huxley

5.1 Overview & Contributions

In the rich and evolving landscape of digital humanities (DH) and cultural heritage (CH), a diverse drapery of user and domain expert practices emerges, reflecting the multifaceted ways in which individuals engage with, interpret, and disseminate the vast reservoirs of cultural data. From scholars conducting careful research to educators crafting engaging narratives for their students, and from curators designing immersive museum experiences to the general public exploring the depths of history and art from the comfort of their homes, the spectrum of users is as broad as it is deep. The richness and complexity of European cultural heritage, with its deep historical roots and wide-ranging expressions across tangible and intangible domains, present both opportunities and challenges for these diverse user groups. Central to these endeavours is the exploration and storytelling of biographies — not only of people but also of objects, places and their compositions, each of which carries its own stories, origins and connections through time. Against this backdrop, the EU-funded *InTaVia* project aims to combine data from multiple national biographies to illuminate the tangible and intangible threads of European CH and to broaden the horizon for academic inquiry and public engagement by breaching national borders of science. This chapter delves into the project's goals, its collaborative approaches and efforts, and the technological underpinnings that make such a synthesis possible.

At the heart of *InTaVia* lies a commitment to faceted visualizations and visualization-based storytelling (VBS) for the visual analysis and communication of findings. Here the protagonists of narratives extend beyond individuals to include objects, locations, and their aggregations. The project seeks to connect structured biographical data from multiple national prosopography projects with related cultural objects, which have been largely stored separately, in an effort to visually integrate and allowing the access multimodal works and lives of artists. These entities, drawn from diverse national and historical contexts, are interlinked within a knowledge graph, unveiling the complex tapestry of relationships and stories that bind them. This approach represents a paradigm shift in how we understand and communicate CH, emphasizing the interconnectedness of our past.

The key to navigating this complex landscape is the project's user-centered design philosophy, which emphasizes simplicity amidst complexity and flexibility within structure. The development of the *InTaVia* prototype was guided by a set of design decisions and visual elements tailored to meet the needs of a wide audience range and accommodate multiple domain-specific practices. This includes multiple linked visualizations organized in flexible layouts, scalable visualizations that support both close and distant reading, geospatial maps, timelines, network graphs, and a storytelling approach that repurposes these visualizations into interactive slideshows. Interdisciplinary workshops have been instrumental in refining these developments for the prototype and helped with prioritizing needs, requirements and interests of users and practical as well as scientific domain-experts.

The linkage between multiple national databases was possible through extensive work on adopting CIDOC-CRM [94] as a universal data model and vocabulary to encode the collective data in a comprehensive knowledge graph. This broad information collection acts as input for the further modules of the *InTaVia* prototype. Through the offered data curation lab module the manual and local editorial of data from the knowledge graph remains possible, as well as the import of local data. This deep implementation within the holistic platform aims to minimize the distance between the data management and following tasks such as visual analytics and the communication via storytelling. This close linkage between those practices also allows for reiterations of them, so that they are not necessarily a purely linear and unidirectional workflow, but rather allows for the ongoing refinement of data, their visualizations and interplay with each other. The result is documented by our synoptic and polyvalent framework, designed to cater to the diverse requirements of the DH and CH communities.

At the core of *InTaVia* is a holistic and iterative workflow that spans data curation, visual analysis, and visualization-based storytelling through interactive slide shows. These slides, enriched with multimedia annotations and organized in various layouts, are crafted with mobile devices in mind, balancing flexibility with user guidance and consistency, aiming to design frameworks and tools that are intuitive yet flexible enough to accommodate the diverse needs of users.

Through collaboration with domain experts, *InTaVia* has explored the potential of storytelling beyond human-centric narratives, questioning whether objects, locations, and communities can serve as captivating heroes within these tales. Within further, four case studies—spanning artists, objects, communities, and locations—illustrate this potential, showcasing unique features and plotlines that exemplify the power of visualization-based storytelling and the capabilities of the *InTaVia* platform.

This holistic and iterative workflow encompasses data curation, visual analysis, and visualization-based storytelling, culminating in interactive slide shows enriched with multimedia annotations. The story creator and story viewer modules exemplify the project's commitment to user-friendliness and consistency, ensuring that the crafted stories are as engaging to explore as they are to create.

As we venture into this chapter, we delve into the collaborative work underpinning *InTaVia*, exploring how it seeks to bridge the gap between complexity and simplicity, and how its design choices aim to accommodate and inspire the manifold user practices that define the digital humanities and cultural heritage fields today. Additionally it reviews existing efforts in visualizing biographical data, discussing various visualization techniques (e.g., maps, graphs, timelines) and their application to both individual and aggregated biographies. Ultimately we reflect on the implications of the presented work for future research and practice in digital humanities and cultural heritage. We consider the potential of artificial intelligence and large language models, the role of extended reality and the digital footprint of objects in biographies, and calls for further development of integrated storytelling technologies.

The overall contribution of the following papers [255, 270, 290] can be summarized as:

Paper 6: **The Multiple Faces of Cultural Heritage: Towards an Integrated Visualization Platform for Tangible and Intangible Cultural Assets** [290] introduces the *InTaVia* project and represents an ambitious effort to bridge the gap between separate collections of cultural heritage data, providing a holistic, integrated view that supports a wide range of research and educational objectives. Through its user-centered design and innovative visual analysis techniques, the project seeks to make complex multimodal cultural heritage data accessible and meaningful to a broad audience of experts and practitioners. - explains work, assessment of requirements and gives outlook over future work and efforts

Paper 7: **A Workflow Approach to Visualization-Based Storytelling with Cultural Heritage Data** [270] discusses the significance and implementation of storytelling as a crucial method for conveying cultural heritage information, emphasizing its application in both physical and digital platforms. The main contribution of the paper revolves around the H2020 project InTaVia, which aims to enhance storytelling in cultural heritage (CH) through a comprehensive workflow that integrates data collection, analysis, and visualization.

Ultimately Paper 8: ***Every Thing Can Be a Hero!* Narrative Visualization of Person, Object, and Other Biographies** [255] presents a comprehensive exploration of the developments in biographical research and digital humanities, highlighting the significant advancements and the pivotal role of storytelling in these fields.

1. **Integration of Diverse Cultural Data:** The project addresses the challenge of integrating siloed, transnational CH data (e.g., images, objects, books, biographies) into a cohesive multimodal knowledge graph, facilitating a comprehensive view of CH that spans both tangible (objects) and intangible (biographies, cultural stories) elements.

2. **Development of a Multifunctional Platform:** *InTaVia* aims to create a platform that supports a wide range of tasks such as querying, creating, compiling, curating, analyzing, and communicating cultural information. This lead to a "Data Curation Lab", a "Visual Analytics Studio", and a "Visual Storytelling Suite" to cater to the needs of various expert users through a multi-functional interface.

3. **User-Centered Design Approach:** The project employs a multi-focal participatory design process involving historians, cultural scientists, galleries, libraries, archives and museums (GLAM) practitioners, and potential users in its development. This approach helps ensure that the platform meets the real-world needs of its users, addressing their specific practices with cultural data.

4. **User-Friendly Interface for Information Search and Curation:** The project introduces an intuitive interface that facilitates the searching and assembling of CH data. This feature is crucial for curating topic-centered data collections and supports the visual analysis required for storytelling, bridging the gap between data exploration and story creation.

5. **Visual Analysis and Synoptic Visualization:** A significant portion of the project focuses on the visual analysis of the integrated cultural data, exploring how to present prosopogra-

phy and object data in a unified manner. The project experiments with various visualization techniques (timelines, maps, network graphs, etc.) to offer synoptic views of cultural actors and objects, facilitating immersive and detailed exploration of cultural heritage.

6. **Visual Analytics Studio and Storytelling Suite:** *InTaVia* offers a suite of tools for data visualization, analysis, and storytelling, enabling users to translate their insights into engaging narratives. This suite supports a range of activities from querying data to creating and curating stories, highlighting the project's holistic approach to storytelling.

7. **Case Studies and Practical Implementation:** The papers detail case studies on artists, objects, groups and locations, showcasing the platform's capability to create compelling narratives based on CH data. This example demonstrates the practical application of *InTaVia*'s workflow, from data exploration to the final storytelling output, providing a tangible illustration of the project's contributions.

8. **Broadening the Scope of Biographies:** The studies highlight a shift from traditional person-focused biographies to include object biographies, emphasizing the interconnectedness between people and objects and their further related entities and fostering post-anthropocentric storytelling. This approach expands the narrative possibilities beyond human protagonists, enabling a richer exploration of cultural narratives that include artworks, institutions, traditions, art schools or even concepts like ecology or technology.

9. **Addressing Challenges in Cultural Heritage Storytelling:** The articles discuss the complex management challenges that arise from dealing with multimodal graphs connecting diverse types of entities, media, and data schemata. It emphasizes the need for visualization designs to carefully balance and mediate between these different elements to avoid overwhelming users. Furthermore the project acknowledges and addresses specific challenges in cultural heritage storytelling, such as the need for interconnectedness in data and the skills required for effective storytelling. Discussed solutions include AI-based data enrichment and user guidance features, aiming to improve the accessibility and impact of visualization-based stories.

The *InTaVia* project represents an ambitious effort to bridge the gap between separate collections of cultural heritage data, providing a holistic, integrated view that supports a wide range of research and educational objectives. Through its user-centered design and innovative visual analysis techniques, the project seeks to make complex multimodal CH data accessible and meaningful to a broad audience of experts and practitioners. Main contributions are in providing an integrated platform that supports the entire workflow of cultural heritage storytelling—from data collection and analysis to the creation of interactive, visualization-based narratives. This approach not only enhances the storytelling process for experts but also aims to make cultural heritage more accessible and engaging for a broader audience by technological advancements and interdisciplinary methods in enriching cultural heritage narratives.

5.2 Paper 6: The Multiple Faces of Cultural Heritage: Towards an Integrated Visualization Platform for Tangible and Intangible Cultural Assets

Eva Mayr[1], Florian Windhager[1], Johannes Liem[1], Samuel Beck[2], Steffen Koch[2], Jakob Kusnick[3] and Stefan Jänicke[3]

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[2] University of Stuttgart, Stuttgart, Germany
[3] University of Southern Denmark, Odense, Denmark

Abstract: *Linking and visualizing multiple types of entities in a DH knowledge graph generates the need to deal with multiple types of data and media modalities both on the designer and the user side. The InTaVia project develops synoptic visual representations for a multimodal historical knowledge graph which draws together transnational data about cultural objects and historical actors. In this paper we reflect on the question how to integrate and mediate the informational and visual affordances of both kinds of cultural data with hybrid designs and show how a user-centered design process can help to ground the required selections and design choices in an empirical procedure.*

5.2.1 Introduction

Over the last decades, many cultural resources (such as images, objects, buildings, books, newspapers, films) have been digitized and stored as digital twins or digital relatives with highly resource-specific metadata in different local databases. To go beyond such siloed in-house databases, a second wave of initiatives aimed for the harmonization and aggregation of similar cultural assets in meta-databases (e.g. Europeana.eu for European cultural heritage). In parallel, automated extraction procedures such as language and image processing started to work their way into aggregated cultural data to extract further metadata attributes or recognize depicted or described entities. Linked data initiatives then started to classify and combine related entities and thus to build up bigger knowledge graphs of multiple types of cultural resources. These complex emerging *multimodal graphs* often connect large numbers of nodes of different entity types, media, and data schemata [142] by multiple types of semantic relations. As such, they provide a rich source for the visual analysis and communication of cultural heritage topics, but also create various complexity management challenges for visualization designers and users alike [282, 318]. On the design side, this includes the challenge to go beyond the confines of multimodal graph visualization and to effectively leverage the whole range of non-relational information (e.g., geographic, temporal, taxonomic, statistical data) for the versatile multi-perspective visualization of such graphs. On the user side, the integration of multiple types of data also broadens the group of possible users (with a broader range of tasks and practices) and increases the cognitive load of their sensemaking efforts—factors, which need to be taken into account in the visualization design and development. This paper explores how to handle such multi-focal development challenges from the viewpoint of the InTaVia project.

The H2020 project InTaVia ("In/Tangible European Heritage – Visual Analysis, Curation and Communication", `https://intavia.eu`) aims to develop a platform for the visual analysis, curation and communication of a large multimodal knowledge graph for cultural heritage data.

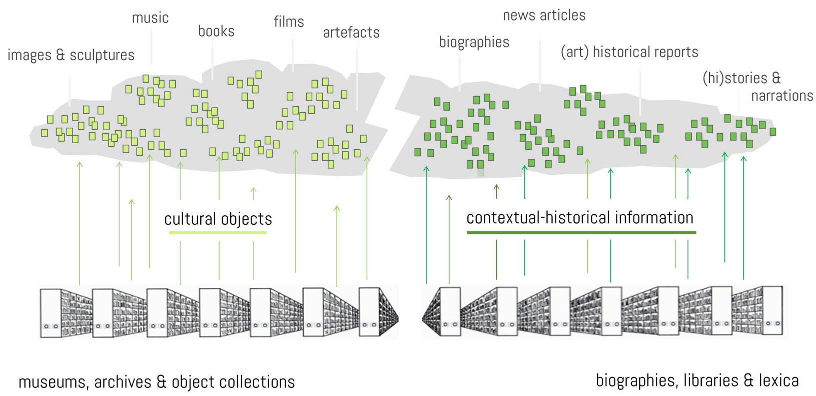

Figure 5.1: The InTaVia project aims to bridge the gap between mostly unconnected cultural data collections, focusing either on tangible cultural objects (left), or intangible knowledge, such as biographies or other cultural (hi)stories (right).

It draws together structured biographical data from multiple national prosopography projects (including Finland, the Netherlands, Austria and Slovenia) and connects this type of structured personal trajectory data to related cultural objects, which have been mostly stored separately, e.g. by aggregators such as Europeana.eu or Wikidata. Thus, for the first time, this project brings together the multimodal works and lives of artists, scientists, engineers, and other notable people—and aims to make this complex graph visually accessible by multiple methods of data visualization.

In the following, this paper sketches out the InTaVia project (Subsection 5.2.2), related work on visualizing multiple types of cultural actors and objects (Subsection 5.2.3) and the handling of related complex design challenges by a user-centered perspective (Subsection 5.2.4). Finally, we provide an outlook on the future InTaVia project development.

5.2.2 Reconciling in/tangible Aspects of Cultural Data in a Multimodal Graph: The InTaVia project

The lives of cultural actors attract scholarly and public attention since centuries [434]—oftentimes in combination with an interest in related cultural objects. Historians and biographers have chronicled the life paths of historical individuals in their cultural contexts and accumulated this knowledge in historical libraries and lexicons in textual form. With the emergence of nation states, biographies of notable citizens have also gained symbolical and political relevance as immaterial historical assets, and became bundled in *national biographies*. These biography collections have recently been transformed by DH initiatives. First and foremost, this has been enabled by technologies of natural language processing, which allow to extract structured entities and interrelations from such historical texts and to make these immaterial aspects of cultural history available in large prosopography projects [129, 356, 380]. The resulting databases comprise named entities like actors, institutions, and locations, all in relations to one another, and chronologically interwoven as massive bundle of event-based sequences[30]. Interfaces to these resources allow to query these entities with regard to various metadata dimensions, and to explore the resulting data selections on an individual (i.e., biographical) or aggregated (i.e., prosopographical) level[381].

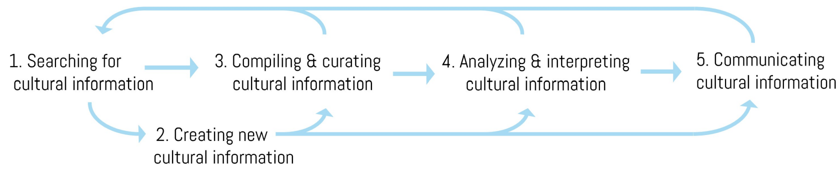

Figure 5.2: Workflows with cultural information frequently connect multiple practices, including search for existing information, creation of new information, data compilation and curation, analysis and interpretation activities, as well as communication and mediation procedures.

The digitization of related *material cultural objects*, on the other hand, has mostly taken a different route: Due to their condensed, textual nature, national biographies rarely include pictures of artworks and objects, such as paintings, sculptures, or manuscripts. These objects thus have rather been assembled by galleries and museums and have been digitized by these institutions to become accessible as digital cultural object collections [212]. For these separated collections, specific types of interfaces have been developed in recent years to grant access to their material stocks and associated metadata and to enable the experience of artworks and objects on the web [371].

Scholars in the arts and humanities, as well as practitioners in galleries, libraries, archives and museums (GLAM) and the interested public thus have very few digital places to go, when it comes to the *synoptic* contemplation of the lives and lifeworks of artists and other cultural actors [456]. Figure 5.9 illustrates, how the division of labor between collectors and custodians of material objects (left), and of biographical or historical-contextual knowledge (right) had a divisive influence on the organization of these assets. While obviously closely related and complementary by nature, both types of data largely remained separated due to institutional and infrastructural constraints. While data models on the object side [97] and general vocabularies for cultural heritage information [108] provide options to link such kinds of information, the two hemispheres remained practically separated from a practical and analytical point of view.

The InTaVia project assumes that experts for cultural information—whether with an academic or a more practical heritage-institutional background—approach cultural information (both about

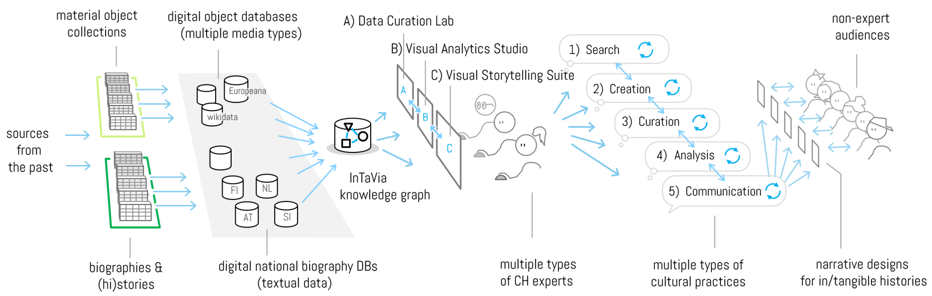

Figure 5.3: Functional architecture of the InTaVia platform, drawing together multiple types of cultural data and media to support multiple user practices.

objects or actors) with multiple tasks and intentions (Figure 5.16): i) They frequently have to query and search for existing cultural information, ii) they create new information for their area of expertise, iii) they compile and curate information from multiple sources, iv) they analyze and interpret this information, and v) they communicate and mediate cultural information to a wide range of audiences. While different cultural experts and professions can specialize on individual steps and practices, most of them connect them into larger sequences and workflows with regard to their subject matter – and do so by following diverse procedural patterns, including iterative and selective sequences with diverse omissions, jumps, and loops.

Figure 5.3 shows how the InTaVia platform reacts to these multi-procedural requirements for both object and biography data, and how it supports multiple types of expert users with their diverse tasks: A multi-functional interface (tightly coupling the modules of a so called "Data Curation Lab", a "Visual Analytics Studio" and a "Visual Storytelling Suite") will i) support search operations, ii) the creation of new structured information, iii) the compilation and curation of data from multiple sources, iv) the visual analysis of selected data, and v) the visual communication of selected constellations by the means of visual storytelling techniques [247]. While visual representations will obviously play a central role for the two latter scenarios, the InTaVia platform will also support activities of querying, data creation, and essential practices of data curation by visual means [455]. In this paper, we will focus on the fourth task, the visual analysis of a multimodal data selection.

5.2.3 Visual Analysis of in/tangible Cultural Data

The visualization of biography data and of cultural collection data arguably constitutes two distinct subfields of visualization for the (digital) humanities. Before we discuss their synoptic visualization, we outline respective data models and state-of-the-art approaches to the visualization of both types of resources individually.

Visualization of Biography Data

Biographical texts are written in a highly specific style, which procedures of natural language processing can parse and transform into series of semantic triples (i.e. named entity relations such as Gustav Klimt was born in Vienna on 1862-07-14, Gustav Klimt is the son of Anna Klimt, Gustav Klimt is the son of Ernst Klimt, Gustav Klimt created "the Kiss" in 1908, etc.). These sequences of structured relational data allow for the visualization of single biographies as timelines, graphs, or trajectories on maps. On an aggregated level, multiple actors can additionally be visualized as trajectory bundles or sets based on shared attributes or relations.

Thus, looking at the prior art, we find a multitude of visualization perspectives: Due to their prominence and availability, map-based visualizations have frequently been adapted for the visualization of biography data [107, 149, 220, 394]. From the relational perspective, network frameworks [14, 136, 378, 383] have been proposed. Attributes of actors or institutions, like professions or fields of cultural production have been visualized by hierarchical or set-based visualization techniques [185, 220, 301, 394, 471]. Due to the multidimensional nature of biographical data, also many mixed method approaches have been developed [14, 107, 185, 220, 301, 383]. As for the visualization of the essential historical data dimension of time, various approaches have been proposed, including timelines [65, 87, 172, 220, 373], animation [1], layer superimposition, or space-

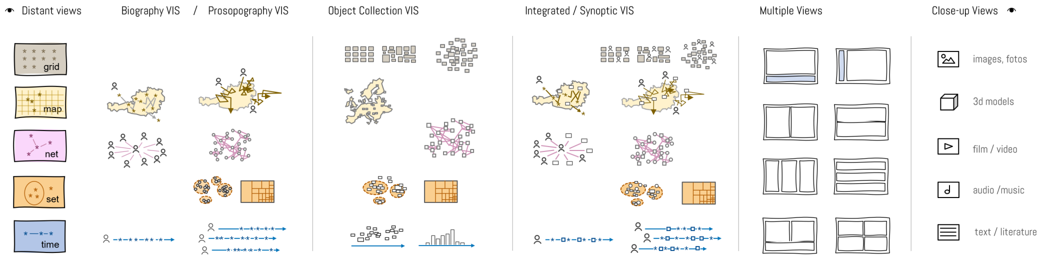

Figure 5.4: Design space of distant views on biographical and prosopographical data (left), object data (center left) hybrid data (center right), and combined as multiple views, all of which should allow immersive transitions into detailed perception or contemplation of cultural objects (right).

time cube representations [107], as well as flexible combinations thereof [288, 289, 457]. The focus of these biography visualization approaches is rather on the structured data than on the original texts (which are sometimes available as linked views) or on related media objects.

Visualization of Cultural Object Data

In contrast to biographical data, cultural object data rarely contains links to other entities or events on a similar level of detail. By contrast, objects are mainly linked to a set of scarce metadata (e.g. creator, date and place of origin) and a lengthy textual object description—as the main focus is on the digital modality-specific representation of the cultural object itself (including pictures, 3D scans, text, music, or videos). Relations to other objects, events or biographies—which could be visualized in a similarly rich relational way to biographical data—are only rarely available digitally [218, 252].

Prominent visualization approaches to digital object collections are (time-oriented) map-, graph- and set-based approaches to distant viewing [224, 458]. Focusing on the media itself, collection visualizations commonly also include object grids, showing objects as ordered thumbnail constellations, which allow for direct access and close-up views on demand. Also other dimensions play an important role when presenting digitized cultural heritage objects visually—including the targeted audience and supported tasks. While domain experts might prefer a search based-interface letting them specify and constrain the digitized object collections they would like to retrieve for specific analyses [240], others might be more interested in exploring (sub)collections freely [452].

Synoptic Visualization of Biography and Object Data

By bringing together the tangible and intangible aspects of cultural heritage data in a multimodal graph (see Subsection 5.2.2), InTaVia aims to pave the way for the integrated handling, analysis and communication of biography and object data. To do so, we have to find ways for their synoptic visualization. While both types of cultural entities contain time-based information, biography data are genuinely time-oriented and temporally structured, while objects commonly are stamped with a date of origin only. Also in biography visualization, the structured (meta)data is the main focus, whereas for cultural objects, the medial representation of the object in all available modalities is a central feature of many visualizations [452].

Figure 5.4 illustrates conceptually how biographical visualizations (left) and visual representation of object collections (center) could be joined into synoptic representations (right). Depending on the number of entities and the analytical focus, different kinds of visual synopsis are possible: Firstly, if the focus is on life events, cultural objects can be represented as markers of their creation events within related biographies on a timeline or a map trajectory. Secondly, if the focus is on entities, objects can be visualized together with actors within graph or set visualizations. Thirdly, if media representations of the cultural actors are available, they could also be integrated into an object collection grid. While all of these ways of synopsis allow the synchronous exploration of cultural actors and cultural objects, none of these options is able to tap into the full potential of both kinds of data—as they focus either on the objects' medial representation or the actors' rich event-relational data, but not on both. A common option to overcome some of these restrictions is the combination of multiple perspectives in a system of *coordinated views*. However, on the design side this multiplies the already complex space of required design choices: Which combinations of (synoptic) views—to be considered for multiple devices—should be offered? Furthermore, how should the temporal data dimension be integrated into other distant views? Across all these encoding questions, the "scalability" of views is of the essence [100, 200, 452, 458]: How can users be enabled to transition from the modality of diagrammatic distant views to the modality of realistic close-up views (or close readings or hearings) which give users access to rich, multimodal media?

By their nature, multimodal knowledge graphs in the humanities unfold a notably complex design space, which the ideal visualization would fill to provide all possible analytical perspectives to users. However, it is well known on the user side that costs of interface complexity can outweigh the benefits of multiperspectivity due to increased cognitive load. On the other hand, the trivial fact of restricted development capacities on designer side also require the reduction of tool complexity, including the deliberate selection or prioritization of views. To rationalize this selection process in the context of InTaVia and ground it empirically, we implemented a multi-focal user-centered design process and gather requirements, validations and iterative feedback from potential tool users.

5.2.4 On Multi-focus Participatory Design

To reduce the complexity of the outlined design space in a rational fashion and to align these selections with the most relevant requirements of future users, InTaVia involves multiple types of users in a formative, user-centered design process on multiple levels: (1) Historians and cultural scientists are part of the project consortium and give continuous feedback. (2) The main concepts and design choices of the InTaVia architecture have been critically discussed in requirement workshops with cultural heritage experts, GLAM practitioners, and potential future users at the beginning of the project. (3) In three iterative test and development phases, developments are critically inspected and evaluated by potential users.

Requirement Workshops

On two different occasions, 41 international participants (21 academics, 13 cultural heritage professionals, and 7 technicians) gave us insights into their practices with different kinds of cultural data and provided us with feedback on the overall architecture and the visualization concepts of

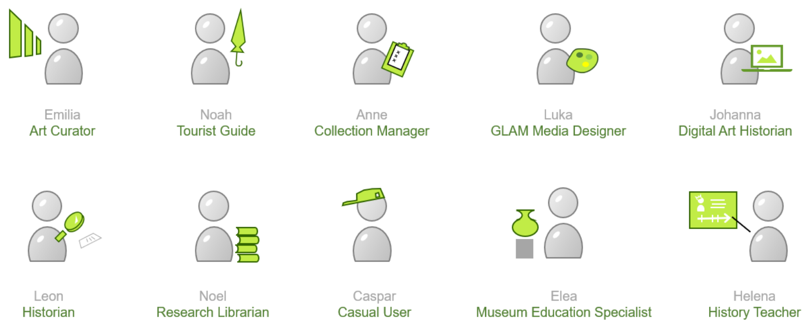

Figure 5.5: Ten personas working with cultural objects and/or actors.

InTaVia. Based on the professional background, the research questions towards cultural actors and objects, we derived and defined ten personas (see Figure 5.5) with distinct user profiles for the diverse fields of cultural information practice. Their diversity already hints at the multitude of possible tasks and practices with respect to InTaVia's multimodal cultural graph.

In a first phase, we asked the experts about their current practices with cultural data. Their *primary tasks and activities* around cultural actors and objects have been (art-)historical (e.g., convey context and provenance of cultural entities, retrieve metadata and general basic information, establish and reveal connections and relationships), infrastructural (e.g., handle large data volumes, store, compare, display, enrich databases and provide access, licensing and copyright), and related to data modeling (e.g., handle uncertainty related to cultural entities, standardize data structures). When asked about *existing deficiencies and constraints* of their current work with cultural information, they named the lack of suitable tools (71%), heterogeneity of the different data and tools (54%), data quality (44%) and siloed or unlinked data (34%)—confirming the need for integrative DH endeavors like the one undertaken in InTaVia.

In a second phase, experts provided feedback on basic development options for the InTaVia platform (see Figure 5.3) and on the outlined complex visualization design space—for object data, biography data, as well as for their hybrid combination. For both *objects* and *actors*, experts were most interested in analyzing their data by timelines, maps, and network visualizations. The value of maps was estimated a bit higher for cultural objects than for cultural actors. For the combined visual analysis of *objects and actors*, the preferred methods were network visualizations, followed by maps and timelines. Overall, experts did express less interest in set visualizations and grid views. One reason for their lower ranking could be that analyzes of groups of persons are less common yet because they are difficult to realize without appropriate data and tools for prosopographical analyses. In a similar way, one participant said that all visualization options sound interesting, but he did not feel himself competent to evaluate them without having tried them. For all kinds of data, experts asked for a flexible interface to choose the most suitable from a set of visualization options, to combine the visualizations as multiple coordinated views, to compare data (by juxtaposition, superimposition, brushing) and to view them in the historic context. Regarding the latter (i.e. for the combined representation of other data dimensions with time) five different options have been discussed, with experts being most interested in coordinated timelines, followed by space-time cube visualizations, animation, color coding and data comics.

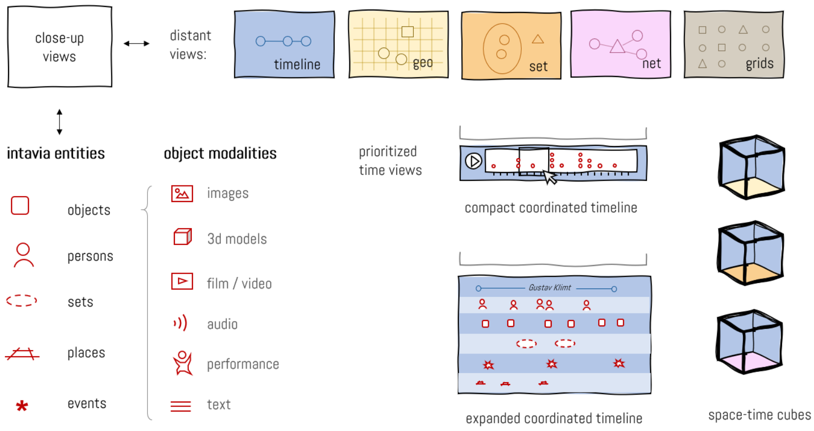

Figure 5.6: Combinatorial building kit for coordinated visualizations.

Iterative Development and User Testing

Based on conceptual considerations and the results of the requirement workshops, an empirically validated, modular building kit has been specified for the visualization development which represents the distant views, which users asked for most: timelines, maps, and networks, followed by sets and grids (see Figure 5.6, top row)—and close-up views on selected entities or multi-modal object types. The prioritized options to represent time are illustrated both as full screen timeline views and as hybrid views (Figure 5.6, lower right), which could be combined with any other (non-temporal) type of view using *multiple view layouts* from Figure 5.4.

As such, (coordinated) *timeline visualizations* will be available at multiple levels of details—depending on the number of displayed actors. A compact timeline view shows entities and events in a stacked fashion. With an expanded view, different types of events are split with regard to related entities and depicted on separate temporal swim-lanes. This detailed view allows also to display medial representations of the actual cultural objects (see Figure 5.6).

Figure 5.7 shows a first snapshot of the ongoing implementation of this visualization system. The initial development focus is on two prioritized views, i.e. maps and (coordinated) timelines, with networks, sets, and various uncertainty representations following in the next development phase.

Similar to the visualization of time, the amount of information displayed on the *map* can be varied by the user (see Figure 5.7, top): from single events (e.g. only places of birth and death for a group of actors) to fine-grained life-trajectories, from life events only to the integrated display of object events. Different types of events are color-coded. Related media will be displayed on demand: By clicking on events, digital object representations or textual paragraphs related to biographical events will be shown as an overlay.

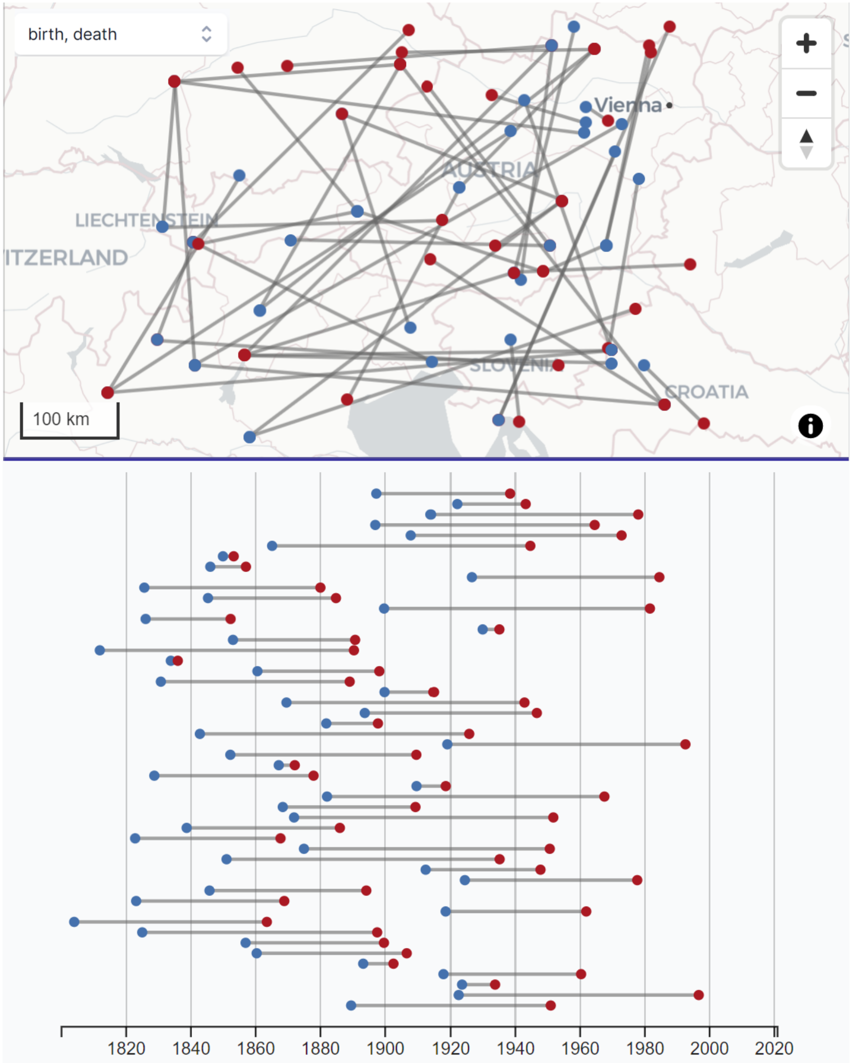

Figure 5.7: First prototype of the map (top) and the compact timeline (bottom) showing persons' birth (blue) and death (red) events.

As a next step, a workshop with expert users has been set up to gather feedback on the first implemented prototypes (see Figure 5.7). Further user workshops will follow in the last project year to evaluate and improve the workflow throughout the whole system—from data curation (including import and creation of data sets), via the interactive visual analysis of data, towards the communication of results through visual storytelling.

5.2.5 Discussion & Outlook

With this paper, we reflected on the development of an interface for the visual analysis of a multimodal knowledge graph for cultural data. We discussed the two main data modalities resulting from historical actors and cultural objects, the specifics of related data models and different modalities of related object media. Biographies are specific kind of texts which automated procedures transform into series of events as person-entity-relations. Objects are represented by multiple types and modalities of media—depending on the kind of object and digitization methods used. Therefore, the current state of the art of visualizing these two kinds of cultural assets—which have been separated until now—commonly also arrive on differently specified visualization techniques and interfaces.

With regard to both data types and the complex InTaVia knowledge graph integrating them, we unfolded a complex design space of visual representation options which we handled, reduced and prioritized with a formative analysis of user perspectives and requirements collected in two requirement workshops. Participating experts showed similar visualization preferences for both kinds of data. For hybrid data selections they want to analyze their distributions and relations, predominantly with time, map and network-based views, but also want close-up access to the actual texts and digitized objects to flexibly transition from the diagrammatic modality of visualizations to the unique, isomorphic experience of artworks and cultural objects.

A first implementation phase is building on these user analyses and builds up InTaVia's 'Visual Analytics Studio' in close interconnection with its neighboring modules.

During the development process we realized how a significant effort of project management, coordination and design discussions was required to manage and handle complexity that arose from phenomena of *multimodality* on multiple levels: Multiple modalities of data sources; a multimodal knowledge graph consisting of multiple types of entities linked by multiple types of semantic relations; cultural objects linked to multiple (types of) media and metadata schemata; and on the user side: multiple cultural heritage experts as users with multiple practices. It is our impression that the relatively new data source of multimodal knowledge graphs in the digital humanities forces such increased investments into efforts of complexity management and that the design of corresponding visualizations has to carefully assess, balance, and mediate between the different affordances of all types of entities—and the different users' practices and requirements regarding each of them. While "complexity" is arguably a feature of every visualization design space, multimodal, graph-based data sources seem to introduce a new order of magnitude which requires a new kind of awareness on the visualization design side, to not get lost in the hyper-modal weeds of expanding design spaces.

Zooming out from the visualization module, we want to close with an *outlook* on the systemic structure of the InTaVia platform: As Figure 5.16 pointed out, the practice of (visual) analysis of DH data rarely takes place in an isolated fashion. By contrast, exploratory data visualization in cultural heritage and DH domains is frequently and intimately interwoven with activities of data querying, data creation and curation, as well as (visual) communication. Correspondingly, the visualization module of the InTaVia platform will be tightly interwoven with two further modules, the so-called "Data Curation Lab" and the "Visual Storytelling Suite" (cf. Figure 5.3 and [247]). Arguably it is only such a systemic architecture, which will allow experts and practitioners to pursue their most diverse types of work with the multimodal data, objects and assets of human culture—and to initiate, (re)direct, loop and iterate their personal workflows according to their situational needs. In closing, Figure 5.8 shows with data collected from the InTaVia requirement workshops how cultural heritage experts interweave and concatenate specific data practices according to their most common workflows. It is the guiding hypothesis of the InTaVia platform development that the emergence of a new generation of complex DH data sources (i.e.

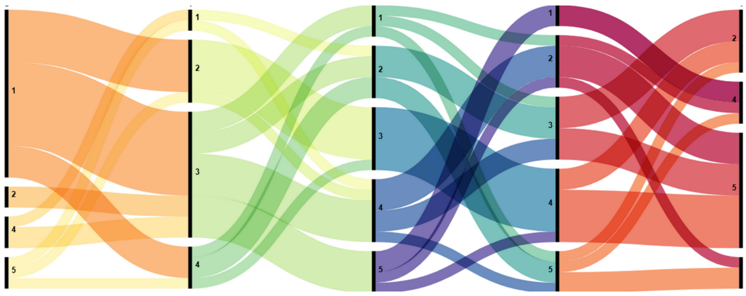

Figure 5.8: Ordering of cultural heritage experts' practices according to most typical workflows (1: searching, 2: creating, 3: compiling & curating, 4: analyzing & interpreting; 5: communicating).

"machine-readable" knowledge graphs) requires advanced efforts to make these aggregations accessible, comprehensible and "human-readable" for various user groups. To also provide a solution for the increased diversity of their practices and requirements, the practice of (inter)linking technologies becomes part of DH tool designers' future remit.

Acknowledgments

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5.3 Paper 7: A Workflow Approach to Visualization-Based Storytelling with Cultural Heritage Data

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Abstract: *Stories are as old as human history—and a powerful means for the engaging communication of information, especially in combination with visualizations. The InTaVia project is built on this intersection and has developed a platform which supports the workflow of cultural heritage experts to create compelling visualization-based stories: From the search for relevant cultural objects and actors in a cultural knowledge graph, to the curation and visual analysis of the selected information, and to the creation of stories based on these data and visualizations, which can be shared with the interested public.*

5.3.1 Introduction

Their omnipresence in human culture—as well as reflections from various scholarly perspectives—make clear: Stories or narratives are among the most essential design strategies for conveying novel, relevant or entertaining information both in present-day culture and throughout human history [38, 105]. Therefore, storytelling is also an important design strategy to communicate cultural heritage information—from the design of physical exhibitions to digital knowledge communication initiatives, and also in hybrid settings.

For the public communication of data-rich subject matters, storytelling has become a ubiquitous topic and strategy in visualization research and development [363, 391]. There are signs for similar developments in arts, humanities, and cultural heritage (CH) fields, where historical sources and information about artists and cultural objects have been digitized and made successively available for a variety of interested user groups.

To fully tap into the potential of these cultural heritage data for visualization-based storytelling, it is necessary to take the intertwined workflows of visual data exploration and story creation into account: Many existing tools provide the means for the actual creation of stories, but do not support preceding practices of searching for CH data, of assembling and curating topic-centered data collections, and for their (visual) analysis. However, stories about cultural heritage topics (be it as an exhibition in a museum or in the digital world) are usually the result of a research process, where curators search for relevant cultural objects and background information, analyze it in depth and finally curate it, before they translate this information and their insights into a compelling narration.

The H2020-project InTaVia (In/Tangible Cultural Heritage: Visual Analysis, Curation & Communication) aims to support this multi-stage workflow by (i) assembling a transnational knowledge graph, which integrates information on cultural objects and cultural actors, (ii) by creating an intuitive interface for searching information within this knowledge graph, (iii) a visual

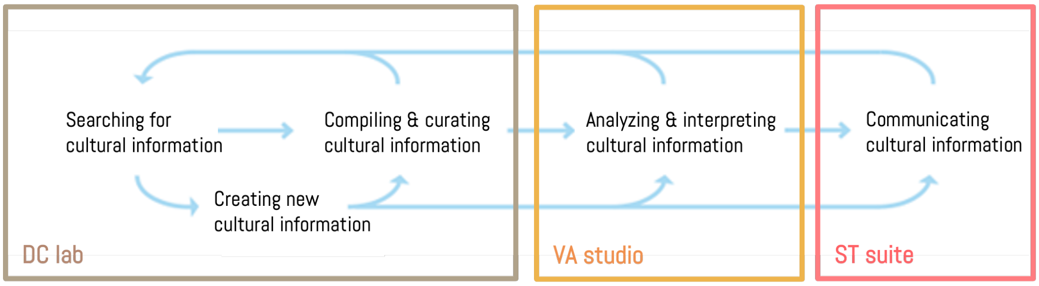


Figure 5.9: Iterative workflow model guiding the development of the InTaVia platform (arrows in blue), annotated with the main modules data curation lab (DC lab), visual analytics studio (VA studio) and storytelling suite (ST suite) that cover each stage of this workflow.

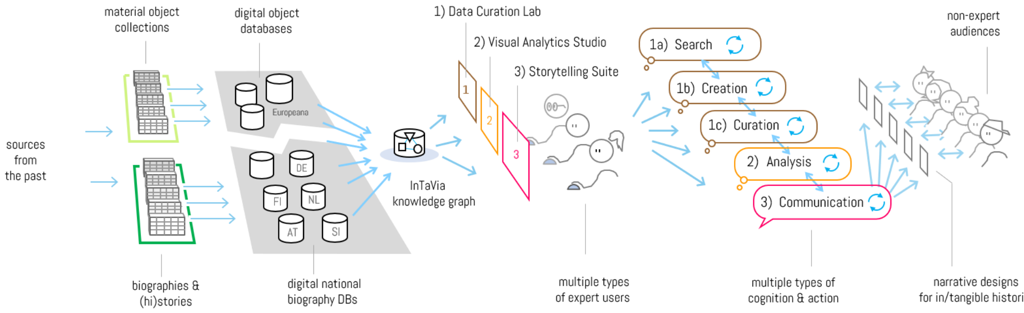


Figure 5.10: Architecture of and information flow within the InTaVia platform, supporting a variety of cultural heritage data practices with visualization-based interfaces, including activities of searching, creating, curating, analyzing, and communicating for a large variety of user groups.

analytics studio for the visual analysis and curation of this information, and finally (iv) a visual storytelling suite for their translation into compelling visualization-based stories Figure 5.9 provides an overview of the practice and workflow model guiding the InTaVia project, to which the overall architecture of the platform responds. The design and development of the platform was informed by ideation and evaluation workshops where we collected feedback from CH domain experts and created case studies with them (e.g., "Traveling with Albrecht Dürer", Subsection 5.3.5).

In the following, we first discuss related work on workflows in visualization-based storytelling. Then we reflect on the implementation of components supporting these workflows within the InTaVia platform as a whole, before we focus on the visualization-based storytelling components that draw together interactive visualizations and rich-media content to interweave them with narrative text annotations. Thus, InTaVia facilitates and fosters data-driven storytelling in a wide range of arts, history and humanities fields, drawing on the modular and sequential architecture of InTaVia to support the whole workflow when creating stories on cultural heritage information.

5.3.2 Workflows in Visualization-Based Storytelling

Considerations from different domains show that combinations of stories and visualizations are well-suited to convey relevant overviews and essential findings or details in an entertaining and memorable way [38, 105, 363, 391]. To efficiently generate such insightful stories based on visualizations, several approaches and workflows were proposed.

Looking at the process of generating visualization-based stories, Dykes [105] describes the procedure as a series of successive steps, which trigger one another "like a line of dominos" (p. 33): Data has to be (i) collected and (ii) organized to (iii) gain insight, which then (iv) can be communicated in a data story to recipients. Even clearer, Lee et al. [262] describe the generation of stories as a three-phased visual data storytelling process: (i) explore the data, (ii) make a story, and (iii) tell the story.

Recent approaches in narrative digital humanities also automatize parts of these processes to automatically generate structured story points from large knowledge bases, or to extract them from texts for their subsequent visualization [26]. In other fields (e.g., data journalism) there are similar visualization-based storytelling systems with similar layout and workflows, such as for the analysis and content extraction of social media data [376]. However, aside from early, experimental work on fully AI-driven story creation, human minds remain the main drivers of the outlined multi-stage workflows.

While the corresponding process models seem to follow a linear order at first sight, the actual workflows require various iterations and cycles of re-exploring and re-collecting further data for identifying and generating a story [262]. This is why a close interconnection of modules for querying, curating, and analyzing data, together with a module for the creation of visualization-based stories might suit these workflows better and has been chosen in the InTaVia project.

5.3.3 The InTaVia Platform: Knowledge Graph, Curation & Visualization

The H2020-project InTaVia ("In/Tangible European Heritage – Visual Analysis, Curation & Communication", `https://intavia.eu`) develops a platform for the visual analysis, curation and communication of CH information. As a main source, it has assembled a transnational and multimodal knowledge graph for cultural heritage data to counteract some of the structural problems resulting from siloed and separated data collections in digital cultural heritage realms [188, 291]. Among these problems, it primarily works to overcome the separation of databases for a) "tangible" cultural objects (such as paintings, sculptures, buildings or literary texts) and b) for "intangible", contextual information, such as the biographical information on cultural actors and artists contained in biographical and prosopographical lexica. The InTaVia knowledge graph draws together data from both types of knowledge collections and currently includes 22,347,784 triples on 111,551 actors from four different European prosopographical data sources (Austria, Finland, the Netherlands, and Slovenia) with data on 172,370 related cultural heritage objects from Wikidata and Europeana [287]. Next to information about persons and cultural heritage objects, the knowledge graph includes entities for institutions (e.g., academies or universities), historical events (e.g., wars), and places. Whether person, assembly, or thing - InTaVia treats each of these entities as a potential protagonist of a story, so that it can have a history of "biographical" events (e.g., birth, creation, travel), including time stamps and relations to other entities.

The system's architecture (Figure 5.16) was designed to support our guiding workflow model (Figure 5.9) with cultural heritage data for users of the InTaVia frontend[1]. For the first step in the

[1] `https://intavia.acdh-dev.oeaw.ac.at/`

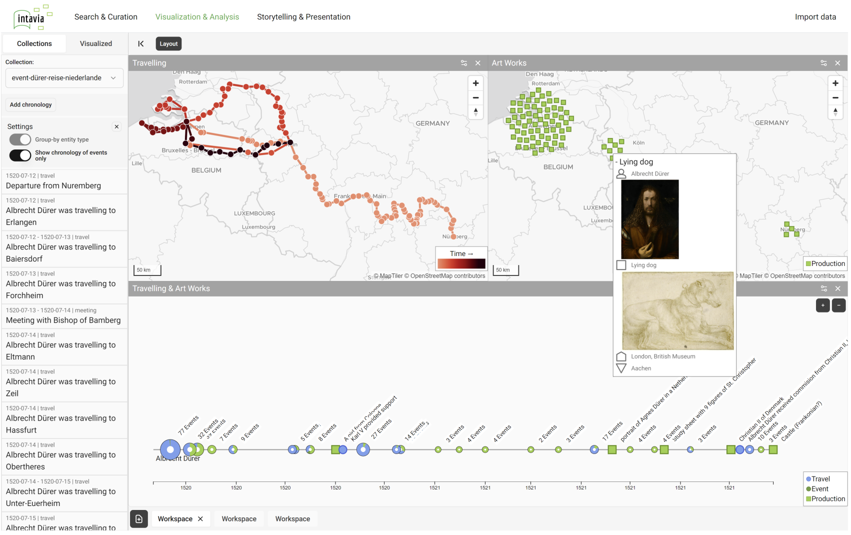


Figure 5.11: Dürer's journey to The Netherlands (1520-1521) in space and time including travel directions, stops and events, and produced art works along the way. Visualized in the Visual Analytics Studio. Based on manually curated data [157].

workflow, querying the data, users can constrain query parameters (e.g., names, occupations, date ranges) either by form fields or by interactive visualizations (visual query builder with "scented widgets" [68, 454]). For the creation (second step) and curation (third step) of data, users are enabled to create new data, or edit and enrich existing data sets locally, in the module of InTaVia's "data curation lab".

For the fourth step in the workflow, data can be visually analyzed either for individual entities from an ego-perspective in a detail view (Figure 5.11) or for multiple entities in linked coordinated views [461]. Different types of interactive visualizations are available based on the specific data and with regard to CH experts' related research questions: timelines, maps, and network visualizations. After they explored and gained insights on the data, users can move to the fifth step of the workflow model and assemble the results of their visually supported query, curation and analysis activities into visualization-based stories.

5.3.4 The InTaVia Storytelling Suite

The Storytelling Suite implements a two-staged storytelling process by the means of two functional sub-modules: The **Story Creator** allows users to create dynamic slideshow-based stories [370] and the **Story Viewer** displays the resulting interactive stories in desktop and mobile browsers.

Both modules are developed as responsive JavaScript web applications using contemporary frameworks, including React [353] and Vue.js [442] for the interface, and MapLibre [283] and D3.js [79] for the interactive visualizations.

Story Creator

The Story Creator is the authoring component of the Visual Storytelling Suite, providing a user-friendly interface for creating and editing slide-based stories enabling the seamless integration of visualizations and other multimedia elements into the story. The data basis for stories is either originating from the InTaVia knowledge graph or from manually curated and imported data, which is then utilized in the following workflow. Users can initiate new stories or re-import previously exported stories. Throughout the project, we developed several multimodal, representative showcases that are available on the overview page. These stories provide a summary of functionalities and aim to inspire the authoring of new stories. By clicking on a story name, users can access the Story Creator and make changes to the content chunks and story flow including their embedded visualizations.

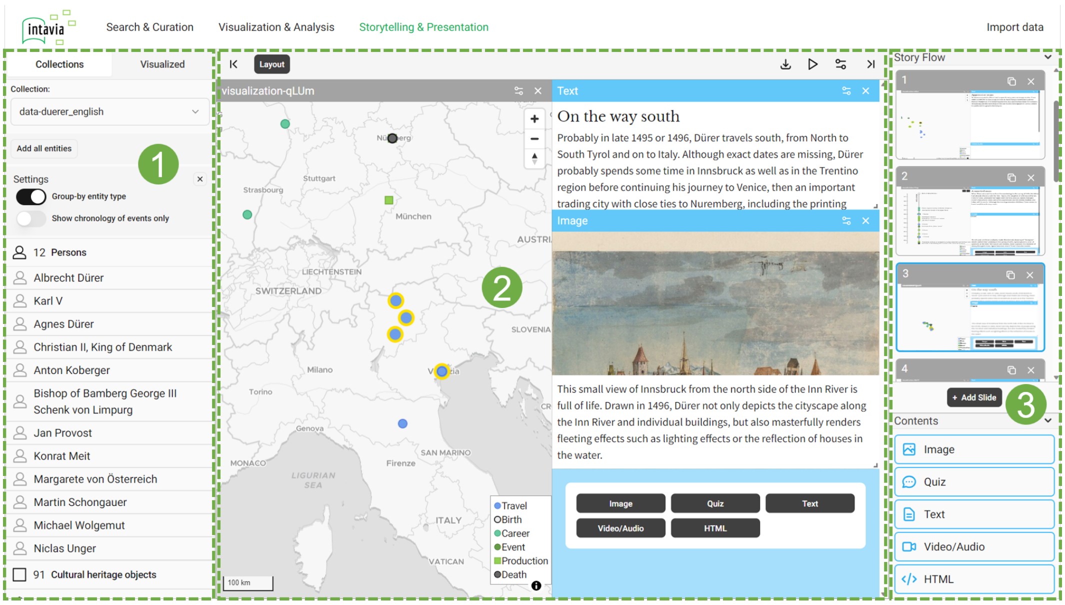


Figure 5.12: Overview of the Story Creator interface: (1) data panel containing collections, entities, and events, (2) main panel for adding visualizations and media content to slides, (3) story flow panel with slide overview and content toolbar. The selected and highlighted event dots on the map are zoomed and panned into the center of the screen during the presentation of slides in the Story Viewer to set the focus on these specific events.

Content Creation and Editing. At the core of the Story Creator is the slide editor (Figure 5.12 (2)), where users define visualizations and content chunks within a slide. Users can either incorporate visualizations created specifically for the story or reuse visualizations created during the prior analysis in the visual analytics studio. Each story slide has a predefined, yet user-selected layout dividing a slide into areas for visualizations and content chunks. We predefined a set of layouts which also work well on mobile devices. To ensure this, we limited the number of possible visualizations to one per slide, whereby a maximum number of two content panels (able to hold multiple elements) is allowed to enable the detailed discourse on multimedia content chunks.

Users can customize the layout of content elements through drag and drop interactions within a slide's grid.

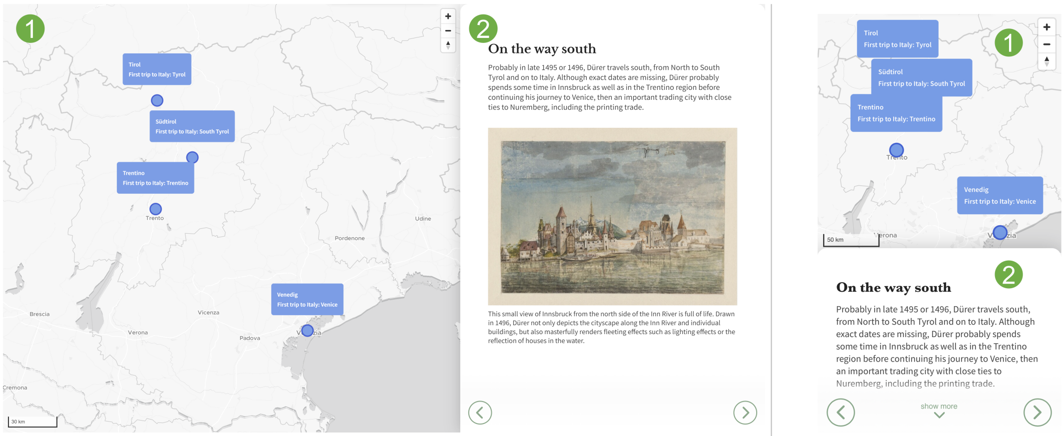
Slide Management and Flow Control. In the story flow panel each slide is represented by a thumbnail card, which can be duplicated, deleted by buttons or rearranged using drag and drop interactions. The Story Creator incorporates a further feature called *nested slides* that allows users to create drill-down stories [391] to optionally provide detailed narration steps between the current and next slide. This feature enhances the storytelling experience by enabling users to present additional information or delve into specific details on demand without interrupting the flow of the main narrative. Nested slides are useful for providing context, explanations, or supplementary content within a specific segment of the story. The inclusion of the nested slides feature empowers users to create multi-layered narratives, offering flexibility and depth in presenting information, and providing a more flexible, immersive and interactive storytelling experience.

Visualizations and Interactions. To facilitate entity subsets, the Story Creator incorporates the data panel (Figure 5.12 (1)) as list of entities and events. From there users can enrich or create new visualizations by adding entities, such as persons or objects, and their related events into them by the press of a button or drag and drop interactions. In the current state of the prototype it is possible to utilize timelines and geo-spatial maps as visualizations within the stories. Since only one visualization per slide is allowed, the choice of the used visualization type depends mainly on the specific focus of the slide either on temporal or geo-spatial contextualization. Both of them are similarly designed to display entities and their related events, supported by various coloring modes to differentiate visually between entity-identities, event-kinds and a temporal color scale [22] ranging from begin to end of the entity's or event set's time period. To minimize visual clutter both visualizations contain the option to cluster events in donut or dot cluster glyphs as shown in Figure 5.11. The various interactive elements of the visualizations and the interface are linked together to react on common interactions such as mouse-overs. Selecting events within the visualizations allows to focus on them during the story viewing to enable seamless transitions with animations throughout the story slides during the presentation in the InTaVia Story Viewer.

Annotations and Content Chunks. By providing additional context and information through annotating slides with multimedia contents such as text, images, and videos users add the narration and increase tangibility. More advanced content types such as multiple-choice quizzes and the HTML-container hold the potential for gamification and further interactivity. Because of the flexible layout options, the various content types can be combined with the visualizations and arranged together. For example multimedia quizzes are possible through the alignment of images/videos and quizzes. The HTML ("Hypertext Markup Language") content type acts as container to include further applications such as three-dimensional object renderings, other web-applications or further visualizations, but also any other content by rendering of HTML. Each of the content chunks is adjustable through a settings dialog to personalize the story's visual elements and create visually compelling and tailored narratives.

Story Viewer

The Story Viewer is an integral part of the Visual Storytelling Suite, designed to enable users to preview and experience the stories created in the Story Creator. The Story Viewer brings the created stories with their configured visualizations and content chunks to life, providing users with an interactive and engaging narrative experience. It enables seamless transitions between slides, smooth visualization rendering, and includes interactive elements, fostering exploration, user engagement and immersion in the storytelling process (Figure 5.13).



(a) Desktop layout (b) Mobile layout

Figure 5.13: Overview of the Story Viewer interface on desktop (left) and mobile devices (right) which organize map (1) and media content (2) either next to each other or in an expandable panel. The four visited and selected stations on Albrecht Dürer's travel to Italy are in the focus and annotated by texts and an image for the tangible narration.

5.3.5 Case Study: Traveling with Albrecht Dürer

We illustrate the different functionalities of the Storytelling Suite with an exemplary story on the influences of Albrecht Dürer's travel activities on his oeuvre, which was generated by the Dürer expert Anja Grebe [153, 157].

Albrecht Dürer (1471-1528) counts among the central figures of Western art history. Thanks to his extensive travel activities and his widely sold prints, his works quickly spread all over the globe and now form the pride of museums and collections worldwide [154]. Dürer is arguably also one of the best biographically documented artists from the early modern times. One of the best documented parts of his life is the so-called Journey to the Netherlands, thanks to a related travel diary and to other contemporary sources [157].

For Albrecht Dürer's life, three major journeys (two to Italy and one to the Netherlands) play an essential role, as they have been deemed an undeniable factor and driver of both the development of Dürer's style and the development of his transnational reputation. Based on a geographical analysis of Dürer's travel activities and related cultural objects, two stories have been generated: a macro story giving an overview on his life and work (see `https://youtu.be/yRzNtX7Dmow`) and a more fine-grained story focusing on his journey to the Netherlands. While these two stories have been developed separately, they could also be presented in a nested fashion, where the user can start from the biographical macro-story first, to explore parts of his life– such as the journey to the Netherlands–in greater detail on demand in nested slides.

5.3.6 Discussion

Storytelling guidelines often assume that an intention or message stands above or behind every story that should be conveyed. However, in order to get there, a large number of practices to process and analyze different sources of information have to be conducted and orchestrated. In the case of cultural heritage topics, the information has to be found, collected and unified, before it can be processed elaborately. InTaVia demonstrates how this workflow can be supported in one integrative platform—enabled by a modular architecture which provides tools to support these different but interrelated steps of the workflow: (i) searching for data on related cultural objects and actors in an integrated knowledge graph; (ii) (re-)creating missing data aspects, (iii) inspecting and curating relevant data; (iv) visually analyzing and representing the data; and (v) creating stories with these data and visualizations—as the presented case study shows in an illustrative manner.

While many of the resulting stories created by cultural heritage experts are compelling, we realized that there are several limitations associated with our workflow:

(1) A decisive factor for the productive exploratory analysis of CH data is a certain richness and interconnection of the knowledge graph—which is not given across the whole reach of the existing InTaVia graph.[2] To overcome this problem, we take several routes: First, we currently aim to increase the interconnectedness of entities by means of different NLP and AI-based enrichment procedures. Secondly, we allow users to import their own datasets from different sources (manually generated or mapped to the InTaVia data model) and use our modules for visual analysis and storytelling on them.

(2) Even though everyone tells stories, not everyone is a skilled storyteller—or knows how to select data and design visualizations. We currently follow several threads and strategies to increase guidance for users: a) We conduct a survey on visualization-based storytelling in the digital humanities to explore and sketch out the corresponding design space. b) We study how specific design features of visualization-based stories influence the attention, interest, and engagement of recipients. c) We design guiding UI elements, which will be included in the interface to support users unfamiliar to visualization-based storytelling.

The outlined workflow approach to visualization-based storytelling offers a chance to reach out to domain-experts in the cultural heritage field, to catalyze intra- and inter-disciplinary collaboration when creating such stories, and to inform and provide the interested public with compelling stories on cultural topics in the context of museums, in cultural tourism, but also in classrooms. By creating compelling visualization-based stories for various users and application domains, we can catch the attention of casual users and create awareness on important cultural topics in a wide range of arts and humanities fields.

[2] For some well-connected clusters within the data, we can demonstrate the feasibility of the approach, e.g. by searching for actors related to Tuusula (an artist community at a lake in Finland) or the Wiener Künstlerhaus (an art association in Vienna).

Acknowledgments

We would like to thank the whole InTaVia team for the excellent and constructive collaboration, which enabled the presented work. The InTaVia project project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101004825.

5.4 Paper 8: *Every Thing Can Be a Hero!* Narrative Visualization of Person, Object, and Other Biographies

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Abstract: *With this paper we introduce a new platform for visualization-based storytelling which aims to close existing gaps for knowledge communication in cultural heritage and digital humanities. On the one hand, data-driven storytelling in these fields has mainly focused on human protagonists, while other essential focus entities (such as artworks and artifacts, institutions, or places) have been neglected. On the other hand, storytelling tools rarely support the larger chains of data practices, which are required to generate and shape the data and visualizations needed for such stories. The InTaVia platform has been developed to bridge these gaps and to support practices of data retrieval, creation, curation, analysis, and communication with coherent visualization support. We illustrate the added value of this open platform with four case studies, focusing on (a) the life of Albrecht Dürer (person biography), (b) the Saliera salt cellar by Benvenuto Cellini (object biography), (c) the artist community of Lake Tuusula (group biography), and (d) the history of the Hofburg building complex in Vienna (place biography). Numerous suggestions for future research arise from this undertaking.*

5.4.1 Introduction

It seems safe to say that biographical research and related communication endeavors have weathered long seasons of critical questioning fairly well. As the smallest possible "micro-analytical" lens of historiography and the humanities, the study of individual biographies comes with the risk of producing rather anecdotal, subjective, and hagiographic (i.e.overly reverential and uncritical) portraits of influential historical elite actors only, while neglecting historical context and the analysis of larger societal (e.g., political, technological, or economic) trends [278, 302, 320, 331]. However, given the wide range of established macro-analytical perspectives in the field of history, biographies keep playing an indispensable role for illustrating their bigger pictures and analyses of broader trends, providing rich and detailed information for historical actors, and thus for "humanizing" history and making its abstract concepts accessible and tangible for a wide range of audiences [358, 443]. In fact, many observers even diagnose a renaissance of the biographical genre, invoking the notion of a "biographical turn" [302, 359]. Among other factors, this development has been driven by the successful (a) *generalization* of the biography concept, but also (b) by the rise of *digital humanities methods and tools*, promoting new ways of biographical investigation and representation.

a) From person to object biographies: Transcending the traditional focus on human actors, the genre of "object biographies" has managed to shift the historical focus from human protagonists to the study of cultural artifacts or things in general, which also fosters the study of human-object interrelations [151, 241]. Gosden and Marshall spell out the consequence of such a hybrid (i.e. person-and-object oriented) approach for the narratological standard lens of anthropocentric hero journeys: "At the heart of the notion of biography are questions about the links between people and things; about the ways meanings and values are accumulated and transformed" [151, p.172]. A first aim of this paper thus is the discussion of consequences for present-day storytelling: *How can we facilitate post-anthropocentric storytelling, where all kinds of entities can become the 'hero' of a cultural narrative?* Related methods will arguably help to not only open up the protagonist position for non-human entities with relevance in digital history and cultural heritage fields (such as artworks, institutions, or places) [81, 177], but also for all sorts of "posthumanist" assemblies in ecology, science, technology, and society contexts [24, 37, 44, 183, 209, 264, 480]. Even further object narratives emerge with their digitization, as multiple facets and information layers are added [479].

b) Digital biography methods, tools, and workflows: In addition to conceptual shifts, digital augmentations of humanities research methods have opened up new options and avenues for biographical research and knowledge communication [45, 46, 89, 90]. Digital language and image processing methods started to work their way into biographical and cultural knowledge collections, to extract large amounts of structured data and to semantically annotate depicted or described entities. Linked data initiatives then started to classify and combine related entities to build up bigger knowledge graphs of multiple types of cultural resources. These graphs often connect large numbers of nodes of different entity types, media, and data schemata by multiple kinds of semantic relations and thus provide a rich source for the visual analysis and (narrative) communication of biographies and cultural heritage topics in general [55, 86, 91].

Research questions: With this paper, we document a recent effort to build on the outlined developments in biographical research, as well as digital humanities (DH) and cultural heritage (CH) fields—and to close existing gaps for related data, visualization, and storytelling tools (see

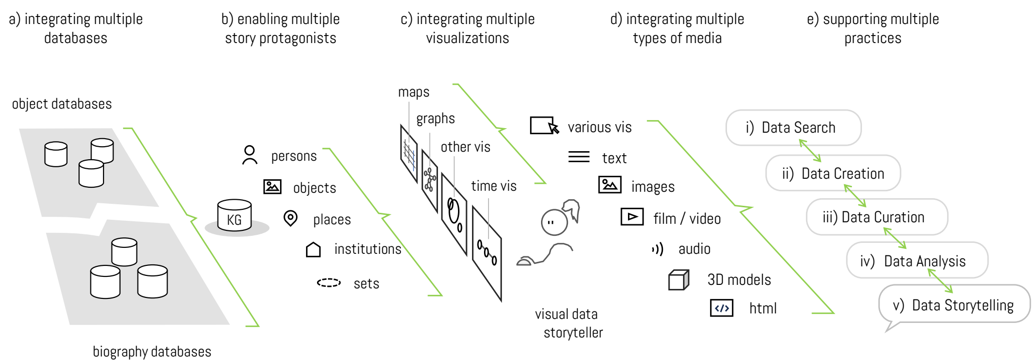


Figure 5.14: Guiding research questions (a-e) for visualization-based storytelling in CH and DH, with a focus on integrating multiple data, media and practices which have been mostly separated so far.

Figure 5.14). A number of *questions and objectives* guided this work within the H2020-project *InTaVia* (`https://www.intavia.eu`):

a) How can we assemble a transnational *knowledge graph*, which draws together existing biography and object data resources?

b) How can we facilitate knowledge communication with data-driven, biographical storytelling? How can we avoid overly human-centered narratives to support storytelling with all sorts of entities relevant in the fields of DH and CH?

c) How can various *visualization methods* support storytelling in an integrated fashion?

d) How can further *media content* enrich these stories?

e) How can we support whole *workflows of data practices* needed for visualization-based storytelling, including data search, creation, curation, and (visual) analysis?

In the following, we reflect on related work of visualizing biographies and telling related stories (Subsection 5.4.2) before we introduce the InTaVia project and the integrated InTaVia knowledge graph. We developed a platform that supports whole workflows with biographical data, including visualization-based storytelling (Subsection 5.4.3). Four case studies illustrate the practical and theoretical potential of such approaches to biographical storytelling (Subsection 5.4.4), while a more general discussion sketches out future challenges for research and professional practice related to DH and CH (Subsection 5.4.5).

5.4.2 Related Work

In CH and DH fields, data visualizations are known for their potential to support the study of both large and small text collections, thus facilitating activities of "close" and "distant reading" [201] or "viewing" [16]. In this section we summarize related efforts with a specific focus on biography data—both for person and object biographies. While doing so, we will look more closely into methods of *narrative* visualization design [391]—as biographical writing naturally translates into narratively structured source data—and proceed from visualizations of person biographies and object biographies to aggregated visual storytelling approaches in these fields.

Person Biography Visualization

As for research into persons' lives (Figure 5.15, top left), various visualization approaches have been utilized to enable the visual investigation and representation of biographical data. Concerning specific *cross-sectional visualization techniques*, we frequently encounter *maps* [85, 350] and *graphs* (i.e., network visualizations), which lend themselves to the visual representation of networks between persons, things, and any other entity relevant for person biographies (such as institutions, places, sets of things) [168, 197, 230, 326, 431, 444, 447]. But also any *other visualization* type can help to analyze specific (e.g. set-typed or statistical) characteristics of biographical data, depending on the analytical focus tasks [139, 219, 224, 267]. These standard views also can be combined as dashboards or multiple coordinated views to represent various facets of biographical data in parallel [198, 222, 378].

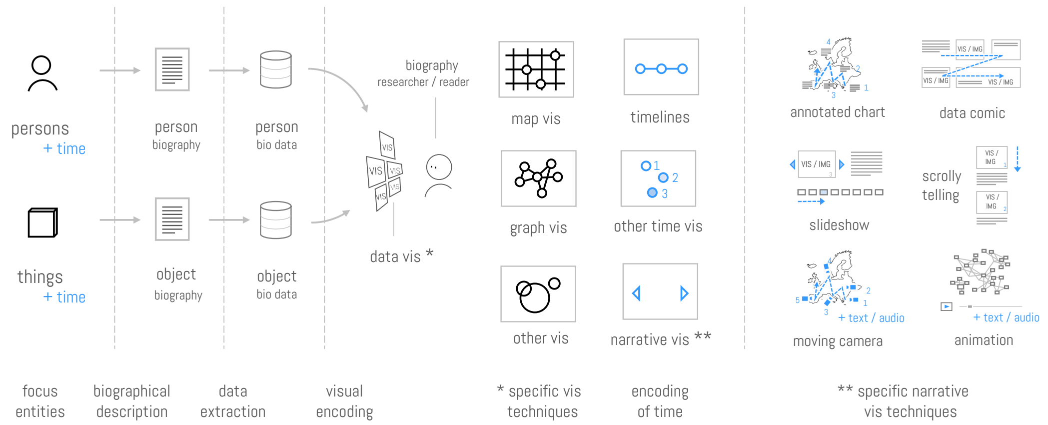


Figure 5.15: Overview of visualization techniques, including narrative visualization designs (center and right), supporting the analysis and communication of biographical data, whether from persons or things (left).

The essential *temporal orientation* of biography data (see Figure 5.15, temporal components highlighted in blue) frequently promotes and requires the *visual encoding of time*—which in its purest form is done by biographical *time visualizations* [7, 67, 219, 220, 245] in either individual, faceted or aggregated fashion [48]. Time visualizations can be easily combined with cross-sectional standard views (e.g., maps with coordinated timelines) for their spatio-temporal enhancement [190, 202, 336, 384], or it is a range of *other encodings* which encode the time-oriented aspects like sequences of events in person biographies. Among them are *color scales* (mapping time to color) [22, 271], *animation* (mapping time to movement) [141], *space-time views* (mapping time to a third dimension) [19, 462], *annotation of dates* (mapping time to numerical symbols) [410], or combinations thereof [149, 457] to balance the distinct strengths and limitations of specific temporal encodings.

How Time-Orientation Translates into Narrative Designs

Closely related to the visualization of time are *narrative designs* (Figure 5.15, right), which are of specific interest to tell the stories of individual lives in a temporally faceted fashion. They can be implemented using a whole toolbox of narrative means, moving visualizations of biography data into the field of "visualization-based storytelling" [251]. Storytelling with data and visualizations is getting more and more popular and related surveys analyze the manifold approaches for "data-driven storytelling" in specific fields such as data journalism [296, 363, 391], data videos [6, 469], scientific publications [427], and DH [251]. Related surveys on visualization-based storytelling analyze further characteristics such as linearity, user freedom, representation, scale, and layout [20, 48, 391, 427], but also emphasize story tropes, genres, and the interactive implementation methods to define the progression through the story thread (e.g. data comic, slideshow, scrollytelling, see Figure 5.15, right) [251, 370].

To convey biographies as visual and interactive stories (e.g., utilizing visualizations in lieu of rich multimedia content and connecting them with a story thread), visualization-based storytelling tools focus on maps [235, 384], timelines [236, 426], graphs [23, 122, 227], or other types of chart visualizations [160, 234, 321]. These tool sets are then used to tell stories of famous biographies [12, 34, 82, 173, 438] or to narrate personal insights related to individual fates [362, 411], which again often represent the (hi)stories and fates of larger groups or collectives [160, 186, 231].

The relevance of such storytelling in CH and DH comes from the natural fit of narrative designs with the omnipresent time-orientation of the data and from manifold options to create compelling collages of information, which interweave the bigger pictures of visualizations with contextual story threads, but also with rich media content such as portraits of persons and scenes from their lives. In the particular cases of cultural actors and artists, biographies are inseparably interconnected with their creations of art [138, 144, 237, 285, 286, 342, 403]; entrepreneurs [125] or military leaders [321] are connected to objects, buildings, or places throughout their live times.

Object Biography Visualization

As for object biographies and histories of things, we find a notably smaller but similar pool of work leveraging visualization techniques for exploring, analyzing, and communicating the "lives of things". Prominent person-centered visualization techniques also dominate this visualization genre: Maps [295], graphs [280, 341, 347], charts [222, 286, 304], and timelines [193, 252] are used to depict various events of object biographies. The matter of time and changing circumstances seem to become more important because of the longer lifetimes of objects throughout centuries, but on the other hand, the dating of events gets more uncertain [224]. Again, color coding [115] or trajectories [207, 336] are used to encode time within other visualizations, like maps. Associated multimedia content is shifting from the depiction of humans to things, using photos, scans [229], (sound) recordings, 3D models [396], or other sorts of "digital twins" of cultural artifacts [474]. Such digital depictions or reproductions of cultural objects—often also addressed as "digital relatives"—can also be analyzed as derivates and cultural artifacts of their own, with specific characteristics and biographies, so that the stories of digital objects (as non-trivial digital extensions of object biographies) becomes a noteworthy subject matter themselves (see Subsection 5.4.5) [15, 479].

Especially the use of 3D modeling to represent physical objects, their evolution, and (hi)stories is prominent: Here, the models are explorable in their three-dimensionality to increase tangibility [25] or animated paths through the models guide the story progression [316, 322]. A few solutions for such 3D storytelling editors to create tours and enrich with further multimedia exist [110, 316, 400], especially within the field of museum exhibition design. The potential for interactive and multi-entity storytelling lies in the disentanglement of hidden stories in-between objects and persons [28, 467]. In museums, the concrete objects are sometimes augmented by interactive (e.g., gamified) elements or visualizations [126, 248] to add more context. Still, physical objects are also used as tangible interfaces (i.e., controllers) between the real and virtual world [69, 128]. Because of the close connection between CH actors and objects, many story examples shed light on a person's creations tightly knit together with their biographies [99, 138, 228, 403]. Similar to these person-centered stories, specific, highlighted examples act as representatives for larger groups forming the (hi)story of whole object-centered topics [126, 140, 253, 286, 402, 437].

From One to Many Entities

While biographical research necessarily starts from selected singular entities, every *contextual* reflection equals a zoom-out shot that reveals their embedding in collections, aggregates, or sets of entities. For persons: families, groups, schools, institutions, etc. (covered by "prosopographical" studies) and for objects: lifework collections, GLAM collections, art-historical formations, and aggregations (covered by collection studies and art history). Visualization can support research in both fields, including prosopography visualization [172, 220, 267, 460], and cultural heritage collection visualization [33, 222, 252, 414, 432, 458]. To create overviews on those collections geospatial origins are illuminated using maps [336, 402, 422] and their development over centuries with timelines [170, 220, 389]. Glyphs are prominently used to depict the distribution of various entities within a grouping (e.g., to avoid visual overlap) on maps [253] or temporal histograms [147]. The inter-linked entities and their evolution within network graphs for whole collections are naturally analyzed within network graphs [197, 267, 280, 341] where clusters and outliers within a larger group become visible. Accompanied is this by supportive visualizations where often the focus lies on the statistical analysis within charts [253, 280, 286] for example via theme rivers and histograms [220, 286] to depict specific characteristics of the collection data sets.

Research and Development Gaps

While the outlined DH and CH visualization field is an emerging and thriving one, various gaps require closer attention to fully support the analysis and storytelling on various entities via visualizations in a comprehensive manner. More specifically, a lack of generalized *multi-protagonist storytelling tools* (e.g., covering persons *and* things from one to many entities), a lack of *multi-visualization-tools* (e.g., covering maps *and* graphs *and* timelines), and a *lack of multi-practice tools* (supporting visual analysis *and* storytelling *and* all sorts of data preprocessing) is asking for more synoptic and functionally integrated solutions.

5.4.3 The InTaVia Platform

The H2020-project "*InTaVia*" (In/Tangible European Heritage: Visual Analysis, Curation & Communication) presents a holistic approach to cultural heritage integration and presentation. By constructing a transnational knowledge graph (Subsubsection 5.4.3), *InTaVia* connects isolated data collections, bridging tangible cultural heritage like paintings and sculptures with intangible cultural heritage such as biographical information. This integration of data on cultural actors and heritage objects from various European sources, along with information on institutions, historical events, and places, offers a more comprehensive view of cultural heritage. The *InTaVia* platform, whose architecture and data flow is illustrated in Figure 5.16, consists of three main modules that support various cultural heritage data practices: The data curation lab (DCL lab, Subsubsection 5.4.3) covers searching, creating, and curating data, the visual analytics studio (VA studio, Subsubsection 5.4.3) provides solutions for analyzing and interpreting data, and the storytelling suite (ST suite, Subsubsection 5.4.3) offers the means to communicate information to non-expert audiences through visual stories. In the following, we will provide more details about each platform module.

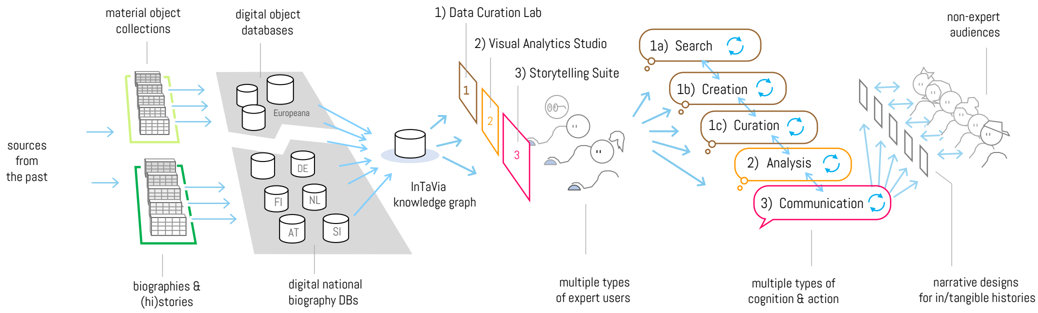


Figure 5.16: Architecture of the InTaVia platform, supporting a variety of cultural heritage data practices with visualization-based interfaces, including activities of searching, creating, curating, analyzing, and communicating for a variety of user groups.

The InTaVia Knowledge Graph

InTaVia brings together data from four national biographical dictionaries: Austria (APIS), Finland (BiographySampo), Slovenia (SBI) and the Netherlands (BiographyNet). These biographical data have been harmonized to match the InTaVia Data Model IDM-RDF [106], which is based on CIDOC CRM [94]. After their integration, for each actor related cultural objects have been retrieved from Europeana and Wikidata.

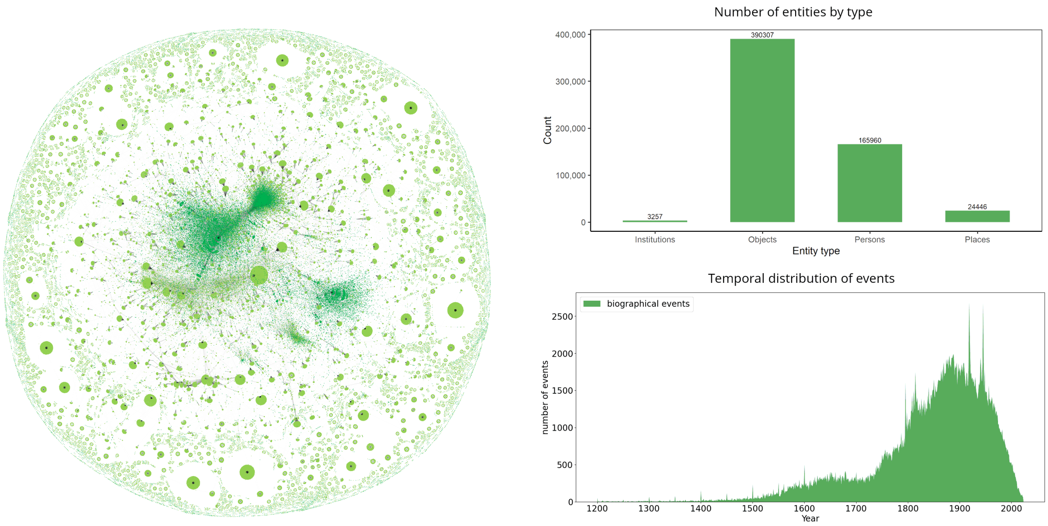
The current *InTaVia* Knowledge Graph contains 24,588,310 triples on 165,960 actors from Austria, Finland, the Netherlands, and Slovenia, 3,257 institutions, 230,068 cultural objects from Europeana and 160,239 from Wikidata, as well as 24,446 places (see Figure 5.17). The majority of the biographical events stem from the 19th and 20th centuries.

The InTaVia Data Curation Lab

The DC lab is the entry point into the *InTaVia* platform by connecting it to the *InTaVia* Knowledge Graph (IKG), offering interfaces to search, inspect, collect, and curate information on the vast CH data that includes persons, objects, institutions, and places. Subsequently, we will give a brief overview of its features.

Querying Data: Users can access the knowledge graph through queries, which can be customized based on specific parameters like text labels, entity types, or relations to specific entities. This allows for targeted searches and retrieval of relevant CH entities. Query results are shown in a list where each entry provides a summary of the respective entity, such as its label, type, and number of related events. Additionally, the result set can be narrowed down further interactively in a visual overview of the returned entities. To manage retrieved entities and reuse them across all platform modules, they can be organized in user-created collections.

Collecting Data: Collections are used throughout the DC lab, VA studio, and ST suite as user-defined sets of entities to save and manage the data that users are working with. They can add individual entities or entire query result sets to a collection. Furthermore, the DC lab allows locally importing data from different sources like Excel sheets or JSON files. It is important to note that this data is not shared with the IKG, nor is the IKG updated when entities are locally edited.



(a) The *InTaVia* Knowledge Graph with actors in dark and objects in light green, generated with Cosmograph [368].

(b) The number of entities by type (top) and temporal distribution of biographical events (bottom) in the *InTaVia* Knowledge Graph.

Figure 5.17: The *InTaVia* Knowledge Graph contains historical actors, cultural objects, institutions, and places—with a focus on the modern era from 1800 onward.

All the available information on an entity is presented on a detail page that includes network, map, and timeline views on their related entities and events, in addition to media files and a biographical text.

Creating & Curating Data: A specialized environment enables users to create and curate data in the DC lab. This step ensures the accuracy and richness of the data from the knowledge graph, integrated with locally imported data. Besides basic entity information like labels, linked URLs, and occupations, users can also enrich an entity's events and relations to other entities. Additionally, they can create new entities not represented in the knowledge graph. These rich curation features give users complete control over their data used for analysis and storytelling in the consequent steps.

The InTaVia Visual Analytics Studio

The VA studio module of the *InTaVia* platform provides temporal, spatial, and relational perspectives on cultural heritage information. To this end, users can create coordinated visualizations in flexible workspaces with adaptable multi-panel layouts that provide synoptic views with several perspectives on the data simultaneously. These tools help understand the connections and patterns within their data collections, making it easier to draw insights.

The three visualization types supported by the VA studio are *maps* (including a space-time-cube option), and *network graphs* and *timelines*. Visualizations can be customized to fit the current information-seeking needs. Multiple alternatives for color encoding (e.g. by entity type or by time) enable different perspectives on the data. Various clustering methods, like donut charts or bee swarm clusters, prevent occlusion and visual clutter in analysis scenarios with many events in

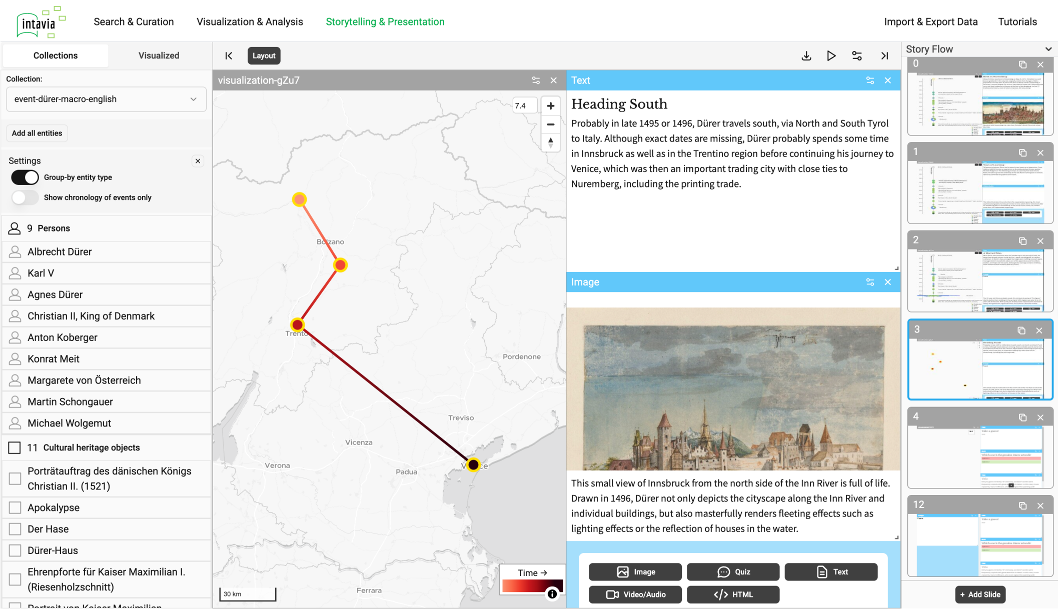


Figure 5.18: The Story Creator interface with the story on Albrecht Dürer. The data panel on the left lists the entities in the collection, the editor in the center allows to create slides with a combination of visualization and multimedia content, and the story flow component on the right allows to manage the slides and the story flow.

close spatial or temporal proximity. In addition, features like visualizing life paths with trajectories on maps or in space-time cubes support demanding analysis tasks. Moreover, the visualizations created in the VA studio can be re-used in the final stage of the workflow by incorporating them into visual stories.

The InTaVia Storytelling Suite

The final step of our workflow involves compiling the insights derived from the analysis into visual stories. This aspect is crucial for presenting cultural heritage information in an engaging and accessible manner. By the possibility of treating each entity (person, object, institution, place) as central figures in their own narratives, *InTaVia* offers a unique and customizable approach towards enhanced accessibility, and enriched user experience by providing a more in-depth, and connected understanding of cultural heritage.

The *Story Creator*, as the first component of the Visual Storytelling Suite, instantiates an innovative concept for crafting multimedia-rich, interactive slideshow-based stories. It integrates several features to enhance the storytelling experience (see Figure 5.18):

Content Creation & Editing: The central component is a slide editor, which allows users to create and organize their content visually. It allows to combine novel or pre-existing visualizations from the VA studio with other media into unique layouts, with a focus on editorial ease of use and well-structured, appealing results.

Slide Management & Flow Control: This feature provides an easy way to manage multiple story slides through a thumbnail-based panel, where users can create, duplicate, delete, or rearrange slides. It is possible to create "nested slides" for additional depth by more detailed substories within the main narrative [391].

Visualizations & Interactions: Regarding different types of visualizations, the Story Creator supports a unique mix of methods: While various "single-method"-tools exist (such as StoryMapJS [235] or TimeLineJS [236]), the narrative assembly of maps, timelines, and network graphs has not been possible before. InTaVia's story creator allows to create stories with all of these visualization types in an interactive fashion (i.e. including details on demand and options for further exploration), which is a crucial aspect to engage an audience. To that end, it uses modern, responsive design elements that are compatible with both desktop and mobile browsers.

Multimedia Content & Combinations: All visualizations can be enriched and combined with various multimedia content, such as text blocks, images, videos, 3D models, and HTML content. The integration of interactive elements such as quizzes or external media and 3D renderings adds to the richness and versatility of the stories.

The *Story Viewer*, as the second major component of the Visual Storytelling Suite, provides the missing link to story audiences and fosters the interactive reception of stories developed with the Story Creator. It brings stories to life through dynamic visual elements, ensures smooth transitions between slides, and delivers high-quality visual renderings in a responsive manner to support mobile devices. Additionally, it incorporates interactive features that significantly enhance user engagement, providing an immersive storytelling experience. Its design focuses on maintaining user interest and involvement, thus setting a new standard for visualization-based storytelling technology.

In its entirety, the Storytelling Suite offers a comprehensive solution for creating engaging, interactive, and visually appealing stories with a first-time combination of multiple visualization types. Its focus on dynamic content, interactivity, and user-friendly design makes it a valuable tool for a wide range of applications, from educational storytelling to cultural tourism, professional presentations, and data-driven narratives.

In conclusion, the holistic workflow of the *InTaVia* platform (illustrated in Figure 5.14, right hand side, and in Figure 5.16 center right) supports multiple practices from finding and curating cultural information to analyzing and exploring it to communicating it in engaging visual narratives. While this appears at first like a straightforward step-by-step process, reality often differs. Usually, many loops and jumps between the steps occur until all details of a biography are explored and understood. While analyzing the data, missing attributes or links might be discovered, and the need for additional visualizations might arise when authoring a visual story. Accordingly, the *InTaVia* platform and our workflow allow seamless switching between DC lab, VA studio, and ST suite to foster this iterative process. Users can enter the workflow at any stage and effortlessly jump between the steps, turning the platform into a powerful multi-practice tool.

5.4.4 Use Cases

Given the outlined combination of features—which stories are possible for which types of "heroes"? This section presents four narrative use cases revolving around different kinds of entities: *persons*, *objects*, *groups*, and *places*. These stories emerged from associated cultural or historical research

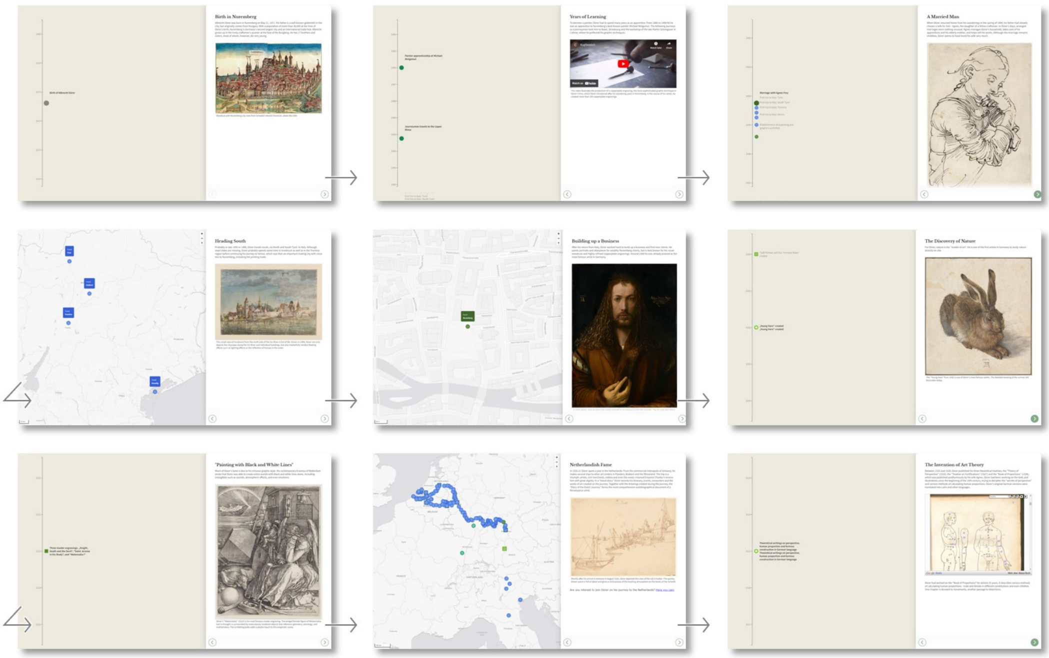


Figure 5.19: Overview of the story on Albrecht Dürer's life.

projects and from co-design processes involving visualization experts, media designers, and domain experts.

Person Biography: Albrecht Dürer (`https://youtu.be/3MRpasJiLqI`)

The story of Albrecht Dürer gives an introduction to his life, including visual representations of his biographical data and related cultural objects. It is targeted at the general public with an interest in art history. The underlying data has been manually curated by Anja Grebe and draws from her prior research on Dürer's life and work. [155, 156]. A sub-story deals with Düerer's journey to the Netherlands, for which she studied his diary, which gives a highly detailed travel record [157]. The biographical data has been enriched with related media on Dürer's artworks and uncertainty information [460], to illustrate how biographical events and movements influenced his artistic ouevre.

Plot: The story recounts the life of the German artist Albrecht Dürer from birth to death. Recipients thus can contemplate important works and turning points of the life of this exceptional artist: his education, his family, the development of his craft, his travels and his international success. A combination of descriptive and narrative texts, visualizations, and images shows how life, business, and artistic work are interrelated. While the main story conveys a biographical overview of important events and travels in Dürer's life, it offers to branch from the main narrative into Dürer's journey to the Netherlands in 1520.

Narrative visualization: The story combines interactive map and timeline visualizations to let readers trace and explore significant events and milestones in Dürer's life, revealing travel patterns and his overall life path. Seamless transitions between selected points in the visualizations on dif-

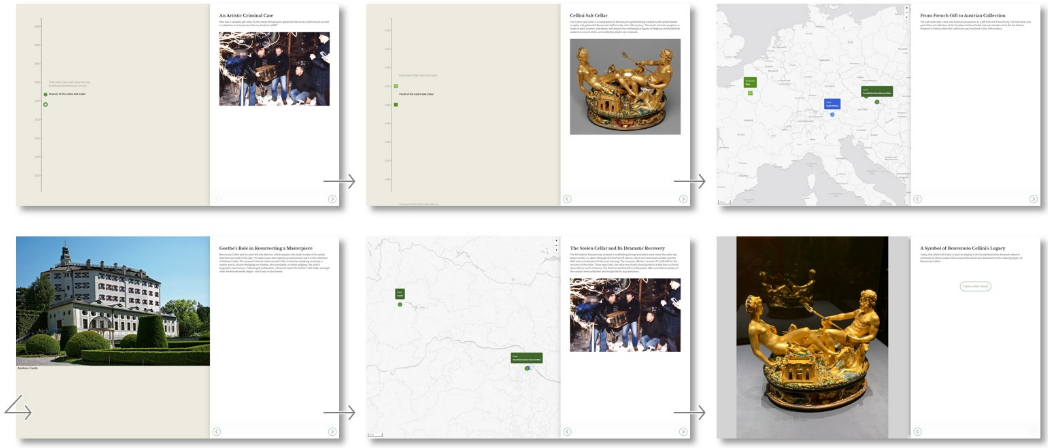


Figure 5.20: Overview of the story on Cellini's Salt Cellar reporting on it's trajectory and theft but also offering insights into it's creator's life.

ferent slides support users in following the course of his life and his travels. While users can consume the story passively and only interact with the slide navigation, they can also freely explore the map and timeline visualizations.

Object Biography: Cellini's Saliera

The Saliera story revolves around a biography of a single cultural heritage object: The golden salt cellar Saliera is a masterpiece of Rennaissance art by the Italian goldsmith Benvenuto Cellini, which came to renwed fame due to its theft and rediscovery. The story is targeted at the general public and interweaves object information with biographical aspects of its artist and information on other related persons. The data has been manually generated by Maximilian Kaiser and enriched by members of the project team for an experimental study on story designs.

Plot: Foreshadowing the recovery of the stolen golden salt cellar in 2006, the history of Cellini's masterpiece is told chronologically: From its first conceptualization by Benvenuto Cellini in the 16th century, where it was deemed unfeasible by the original sponsor, to its actual production for the French king Francis I, who gave it to the Austrian archduke as a present. Later on, it became forgotten until J.W. Goethe translated Cellini's biography into German and interest in the artist's work arose again due to his wild and turbulent life, mixing high art with murder and other crimes. Eventually, the Saliera became one of the most prominent exhibits at the Art Historical Museum in Vienna. In 2003, during construction work at the museum's facade, it was stolen from the museum in a spectacular heist, to be recovered again after years of investigations in a wood near Vienna, so that it is now on display again.

Narrative visualization: Visualizations mainly focus on the object data and depict the biography on a timeline and on a map, enabling users to trace and interactively explore significant events and milestones of Cellini's Saliera, revealing transportation patterns and important events.

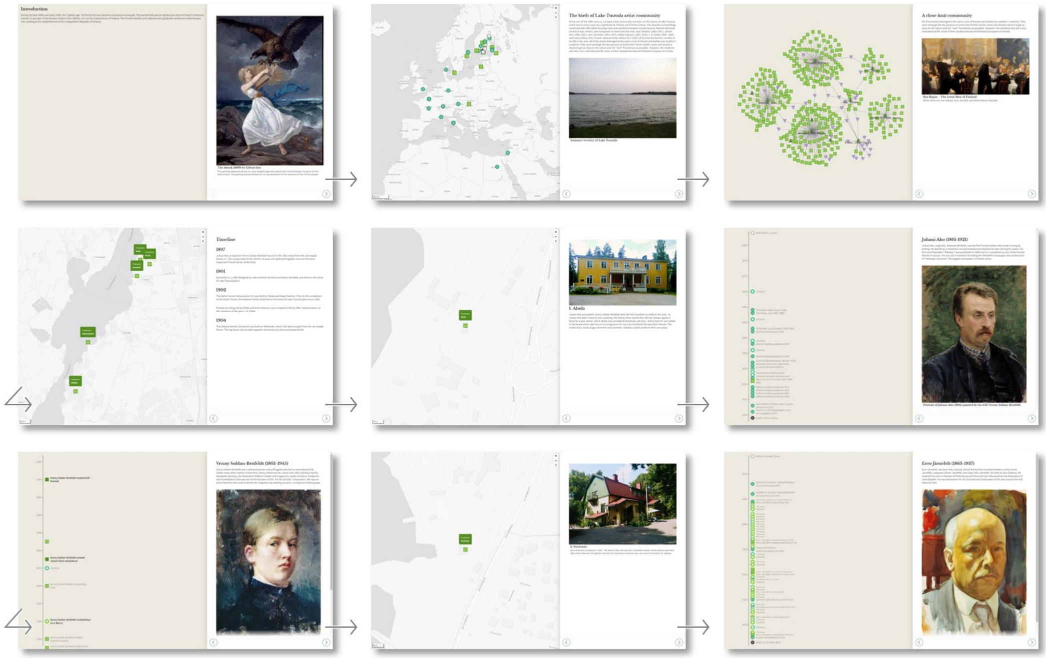


Figure 5.21: Overview of the story on the Tuusula lake community shedding light on the historical development of a close knit artist community settling around a Finish lake.

Set Biography: Tuusula Lake (https://youtu.be/_9gr62cg85w)

This story centers on a prosopographic data set, aggregating the biographies of multiple persons related to the Finnish Lake Tuusula into a collective narrative. The target audience is the general public with an interest in art and cultural history. The biographical information of the artists has been gathered from the Intavia Knowledge Graph (IKG). New cultural objects for the houses have been created and merged with the data from the IKG [342].

Plot: The story focuses on a group of influential Finnish artists who settled to live around Lake Tuusula in the early 20th century—and on the creative network generated among them. After an introduction, the recipient is guided to important places around Lake Tuusula and introduced to the actors, important events in their lives, and some of their works.

Narrative visualization: The story starts with two visualizations introducing the Tuusula lake community as a group: (1) A map visualization conveys the cosmopolitan character of the community, which was active all over Europe. (2) A network visualization of all important actors of the community depicts how close-knit the artistic collective around the lake was, leading to influences and paintings of each other.

After setting the scene, the story focuses on a map of Lake Tuusula, which guides the user around the artists' residences along the shore. For each artist, a timeline illustrates the most important life events—with a selection of them highlighted, while the others can be explored by the readers.

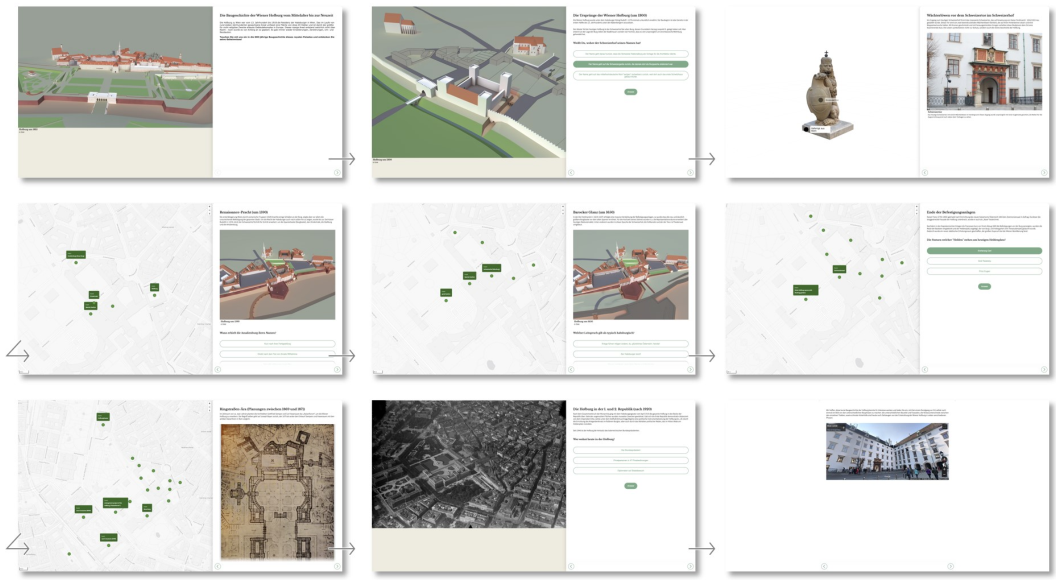


Figure 5.22: Overview of the story on the Hofburg castle in Vienna, Austria, utilizing 3D renderings of historical stages of the castle and a further interactive 3D model plus augmented reality experiment.

Place Biography: The Building History of the Vienna Hofburg (`https://youtu.be/VfMtttzMtJ4`)

The Hofburg story is both a place and a complex architectural object biography in Vienna, targeting the general public with an interest in imperial and cultural history, as well as tourists visiting the building complex of the Vienna Hofburg. Though it appears to be one coherent building complex today, it was built in steps and phases over centuries as a symbol of the Habsburgs' power. The data has been manually generated by Richard Kurdiovsky and project colleagues and is based on a major research project by the Austrian Academy of Sciences [216, 246, 277, 390, 418, 451].

Plot: The story tells the construction history of the Hofburg in Vienna from its founding in the 13th century until today. Over the course of centuries, it developed from a basic fortified castle to a huge palatial building complex as the power and empire of the Habsburg monarchy grew. Visual representations of different construction phases and building objects are shown in historic drawings, plans, prints, and 3D renderings. This story also branches into a detailed description of the Hofburg's building state around 1590 (which could be added for each of the presented building states in a similar way).

Narrative visualization: As the story focuses on a whole place of imperial living, a map visualization is the central visualization component, around which the story unfolds. It enables viewers to better comprehend the location of different buildings and the growing size of the palatial building complex. The map is complemented by 3D renderings of the Hofburg, which visualize the size of the building complex at each development stage. At the end of the story, users can explore the building complex with the 3D engine of Google Streetview.

Comparative Summary

The stories outlined above center on different kinds of heroes: a person (Albrecht Dürer), an object (Cellini's Saliera), a place (the Vienna Hofburg), and a group (the Tuusula Lake community). While each story has its unique characteristics, we can observe several commonalities:

(1) *Setting*: At the beginning of each story, the spot is put on a "hero", setting the scene and introducing the main actor. Depending on the entity type, different kinds of information are given: For the person it is the life range and occupation, for the object it is the temporal and regional origin together with its creator, for a place it is the spatial context, and for the group it is the members. But independent of entity type, the initial emphasis of all settings is on the importance and specificity of the protagonists: Why are they of interest? Why are their stories told and why should the recipient care and follow the narratives?

(2) *Visualization*: Due to the inherent temporal nature of biographies, all stories make use of time visualizations, which greatly helps to guide viewers through important events and stages of the heroes' lives chronologically. Depending on the entity type, other types of visualizations then provide complementary support for the comprehension of a story: For instance, a network visualization emphasizes how a group of actors is related, while maps make movement patterns transparent and help to locate places.

(3) *Linking the visualization with the story flow*: For visualization-based stories, users should be supported to create links between the textual paragraphs which mostly carry the narrative and interconnect the visualizations and other media [260, 459, 477]. In our use cases this is realized threefold: By placing related text blocks and visualizations side by side, by highlighting relevant data points (places on the map or events on the timeline), and by showing transitions between different places or events.

(4) *User Experience & Engagement*: How engaging a story is, does not depend on the kind of entity, but rather on narrative design patterns: For example, whether story hooks are presented at the outset or in the midst of a setting, whether tension is built up successively and developed by a narrative arc, or whether surprising turns or facts are presented within the story, which (re)kindle the viewer's attention . Arguably, story recipients can more easily identify themselves with human actors than with a salt cellar or with a building. However, by changing our perspective or by combining multiple types of entities we can "humanize" and dramatize such stories, as is shown in the Saliera story, where its creator is prominently featured. We will come back to this point in the discussion.

5.4.5 Discussion

Various questions arising from the outlined endeavor seem to be of general relevance for storytelling within DH and CH fields. We start from the assertion raised in the paper title and discuss questions of scalability and visualization design, but also challenges and opportunities opened up by novel technologies like Large Language Models, Artificial Intelligence and Mixed Reality. Finally, we elaborate on implications for DH and CH practice.

Can Every Thing be a Hero? The InTaVia project created a knowledge graph and a platform that allows modeling visualization-based stories on any kind of entity available as a "node" in the graph. Obviously, this does not imply that each (kind of) hero story has to be equally successful in terms of user engagement and learning. User engagement is oftentimes questioned when it comes to non-human entities (e.g. physical CH objects). To address this question, we recently conducted a pilot study in which we compared stories on human actors with stories on cultural objects [292]. For object stories, the study participants indeed reported slightly lower levels of engagement. A possible explanation could be that objects are more frequently perceived as passive entities, whose course is only influenced by others' actions. Still, objects such as artworks, weapons or tools obviously influence persons and other entities and can be analyzed as protagonists—we just have to shift our perspective. But also the dominant form of metadata for CH objects makes their "biographical" analysis and representation difficult: Objects frequently have only one (or a few) structured events ("has been created by"), whereas person biographies are (even if frequently also only in textual form) a more event-focused genre. Further interesting object events (such as restorations, modifications, sale, theft, destruction, interpretations or inspirations) and their involved related entities are rarely documented. However, biographical visualizations depend on rich and structured event data—no matter which kind of entity. How much engagement and interest a specific (type of) hero triggers, depends also on the recipient of the story. For example, identification with the story protagonist is known to increase engagement. But also the right level of story complexity, which matches the recipient's available cognitive resources for processing and sensemaking—and deviations both upward or downward put a positive reception in jeopardy.

Advancements in technology, such as AI-driven data analysis, natural language processing, and machine learning, empower storytellers to uncover and present complex narratives around non-traditional protagonists which are adapted to a user's needs and interests. These technologies can identify connections, patterns, and significant aspects that might not be immediately apparent, thereby elevating various entities to the role of the protagonist in their unique narratives. Also their ability to generate new (fictional) content impersonating different roles and styles can spark creativity or streamline storylines [377]. Furthermore, identification with a protagonist can also be triggered by tangible cultural objects or places, which are augmented by visualization-based stories. Such extended realities blur the barriers between the digital and real story worlds and allow to directly link physical objects and places of cultural importance to their digital derivates, further digital multimedia content, and visualization-based stories.

AI and Large Language Models: The use of advanced Artificial Intelligence (AI) and Large Language Models (LLMs) is of crucial importance to CH research [131] and visualization-based storytelling [26, 166]. Hence, it may also be promising for biographical storytelling and introduce advantages, especially in detecting and combining the complex connections and interrelations between cultural objects and their historical context rendered in large data sets, knowledge graphs or unstructured sources. Using generative language models in the creative writing process can assist in generating narrative content [472], which is relevant to authoring interconnected stories in CH. AI algorithms are proficient in pattern recognition, which allows them to reveal concealed links between an object and related entities, such as other objects, persons, places, or events. This proficiency may enhance the storytelling authoring process, providing a more intricate and interconnected narrative. The technologies' capacity to process and analyze large datasets can unveil intricate historical and cultural relationships, providing profound insights into the journey and impact of each object. The use of AI and LLMs may allow for dynamic, context-driven, and real-time adjusted storytelling instead of providing sequentially rendered, fixed story content. However, it is important to take into account potential historical inaccuracy and missing cultural sensitivity to ensure that the stories they help create are informative, respectful, and reliable. Thus, future research must focus on developing the integration of AI technology into object-driven storytelling while also addressing its inherent risks, such as inaccuracy and unreliability.

Extended Reality (XR), Object Presence, and the Metaverse: The utilization of mobile applications and AR in CH settings, such as museums or heritage and archaeology sites, holds great potential for more immersive and engaging story experiences [71, 332, 334]. In analogue exhibition settings, objects can be points of departure for storytelling, when they are augmented with digital information through smartphones and wearable technology. As such, story audiences can directly interact with real objects on site and gain from the 'aura' of original artworks, which promises to enable richer, more meaningful experiences and deeper understandings of the object's significance and history [367]. The rapid growth of XR and the Metaverse presents new opportunities for storytelling in the CH sector. The availability of not only 3D objects, but also a rich, interactive, persistent, and fully immersive environments for object and story interaction opens up deeper possibilities that still need to be researched and developed. Stories about objects or other entities traveling through time and space, interacting with different people, and being involved in events can be mapped onto "space-time cubes" [463]. Thereby new options for hybrid knowledge exploration and navigation and new forms of collaborative access emerge [263].

Digital Representations as Extensions of (Object) Biographies: The digital age has redefined and reframed the concept of object biographies, considering not only the historical and physical journey of an object but also its digital footprint [479]. Digital derivatives and user-generated content *enhance* the biographies of objects, offering insights into changing eras, circumstances, and the entities connected to these objects. This digital dimension adds layers to the narrative, which make it richer and more complex. The proliferation of social media and digital platforms facilitates the continuous *recreation* of objects and the inspiration for further works. This digital presence ensures that objects reach a wider audience and engage in an ongoing process of *re-interpretation* and re-imagination, which contribute to the evolving biography of an object, which again re-shape the perception and significance of the object over time. But also the objects themselves often represent broader *narratives or values*, such as superiority over other nations. Their digital representations reinforce and disseminate these narratives to a global audience and open the discussion of their changing conception and debate.

However, this digital reproduction and representation of objects raise questions about *ownership, copyright, and privacy*. As objects' biographies expand in the digital realm, navigating the legal and ethical implications of digital ownership— especially with easily available generative AI possibilities—becomes increasingly complex. This multifaceted nature of object biographies in the digital age, emphasizes how digital platforms and user engagement not only document but also actively contribute to the life histories of objects.

Implications for Practice: The current state of the CH industry indicates that GLAM institutions have successfully incorporated digital databases and tools for mediation, education, and storytelling. Museums, for example, are increasingly offering on-site mobile apps and interactive media experiences to enrich visitors' knowledge and experience of their exhibits. As museums are mostly object-focused, they are primary candidates for using multi-entity storytelling methods as discussed in this article. However, some challenges and issues need to be addressed in order to fully exploit the existing potential. These include (1) skills, (2) data accessibility, and (3) technology: (1) Concerning *skills*, cultural educators and other GLAM professionals must broaden and enhance their competencies for different storytelling formats, media types, interaction modes, and data relationships [3]. An analysis of digital storytelling practices highlight the impact of technology on story production and the need to increase data and tool literacy [92]. (2) Concerning *data accessibility*, CH practitioners still rarely exploit the opportunities of multi-entity storytelling based on biographies of objects and other entities. To achieve this, accessibility, connectivity, and interoperability of cultural databases are needed—which are currently highly dispersed, incompatible, and isolated. The importance of interoperable digital platforms for the storage, processing, and visualization of CH data—and improvements of data accessibility—are also crucial for the sustainable and inclusive valorization of CH [276]. The presented InTaVia Knowledge Graph is a first step towards this goal, but has to be expanded to include further databases and biographies with more structured events. (3) Concerning available *technologies*, more powerful and accessible digital solutions are required for the creation of engaging DH and CH stories that accommodate various content types and user interactions [366]. Thus, the editing of dynamic stories linked to various CH and DH entities requires novel editing tools to handle whole workflows together with their conceptual and informational complexity. In this context, it will be key to refine and adapt multi-level tools such as InTaVia and to ensure their functionality beyond the maturity level of research prototypes.

5.4.6 Conclusion

Storytelling has been said to drive the development and reproduction of human cultures and knowledge since prehistoric times [2]. Spectacular changes in media and information technology—evolving at an ever-accelerating pace—have not diminished the relevance and dominance of stories as a communication form a bit, but multiplied ways in which cultural narratives can unfold and reproduce, including spectacular options for their multimodal and immersive expression.

With this paper, we started from work in the field of visualization-based storytelling for biography research—and made the case for orchestrated integration efforts—to create *more synoptic and integrated storytelling technologies* for DH and CH data domains. The InTaVia project realized such a platform by following five development strategies which allowed to integrate multiple data and tool dimensions, which have been separated before:

a) *multi-database*: The platform draws together multiple types of databases (i.e. on cultural persons *and* objects) into a coherent knowledge graph.

b) *multi-protagonist*: InTaVia generalizes the protagonist role to cover multiple types of entities in CH and DH domains.

c) *multi-visualization*: The platform covers and combines multiple visualization types (i.e., maps, graphs, and timelines), which have not been integrated by storytelling tools before.

d) *multi-media*: The storytelling suite combines and leverages the power of multiple kinds of media (in addition to visualizations also textual elements, images, audio, video, interactive 3D models, HTML content, etc.).

e) *multi-practice*: Finally, the platform follows a holistic, workflow-oriented design, supporting multiple types of cultural data practices from information creation to analysis and communication.

We consider such synoptic and integrative design approaches and resulting tools to be of high relevance for CH and DH, but also for adjacent data and application fields, including educational and social sciences or data journalism. They provide scholars and practitioners of these professions with powerful allround tools, connect them to open data collections and cover all relevant processing practices, while being engineered for the efficient creation of highly context-specific results.

With current AI developments shifting the ground under most DH, CH, and visualization technologies in real-time, projections for the relevance of all sorts of methods are well-advised to proceed cautiously and remain deliberately open for disruptive story turns. However, given the known limitations of generative AI, it stands to reason that expert-driven storytelling technologies such as InTaVia will play an important and indispensable role for trustworthy cultural knowledge communication until further notice.

Acknowledgments

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6 Overall Discussion and Summary

It is possible to highlight several overarching observations and open problems for future work related to the implemented approaches described in this thesis and included papers.

6.1 Domain Specific and Controlled Vocabulary

During my work with musical instruments and their corresponding works, I encountered the significant challenge of navigating through different vocabularies for the first time. This diversity necessitated the establishment of a comprehensive system and a dedicated database designed to facilitate translations across various languages and datasets. This endeavor was crucial for ensuring the seamless integration and understanding of the information from different sources.

In the process, I also faced the issue of information loss during data transformations. A notable example of this occurred with the "Musical Instruments Museum Online" (MIMO) [1] project when it merged with Europeana, where a significant amount of information was lost during the transition from one format (LIDO) to a newer one (EDM). Crucially for our use case on object biographies, detailed information on events, such as the modifications to the objects, were dropped because they were not supported by the newer format [116]. This loss highlighted the delicate balance between updating data handling processes and preserving the integrity of the information.

Biological datasets presented a different set of challenges, primarily due to the inconsistency in species names—whether they were renamed or only listed by their common trade names—and country identifiers. Such variability complicates the task of maintaining accurate and consistent data records across studies and repositories.

In the context of *InTaVia*, we encountered substantial difficulties with the varying descriptions and interpretations of data, as well as differing levels of precision across national datasets. These discrepancies posed significant obstacles to harmonizing data and extracting meaningful insights.

Even domain experts struggled significantly with the combined data of the knowledge graph accessed through the *InTaVia*frontend prototype, primarily because the event information and other descriptions were either too specific (in one language), making them inapplicable in broader contexts, or too general to be of practical use (in other languages). This situation underscored the challenges of achieving an optimal level of detail that is both informative and broadly applicable via a controlled vocabulary.

The rapid advancements in machine learning and labeling-based approaches, as discussed by Meinecke [299], alongside the development of large language models (LLMs), offer promising solutions to these challenges. These technologies have the potential to account for context, which can significantly enhance the accuracy and relevance of data translations and transformations.

[1] https://www.mimo-international.com/MIMO/

Their ability to interpret and adjust to varying levels of specificity and generalization could revolutionize how we manage and understand complex datasets across different domains.

6.2 Storytellers and Visualizers

Already during my master's thesis, which focused on the interactive and gamified visualization of musical instruments digitized through computed tomography, we explored the concept of creating scenes that narrate the story of an object and its construction [249, 386]. This idea was further enriched by the contributions of instrument makers, musicologists, and restorers who, through their interactions with the instruments in virtual reality (VR) and augmented reality (AR), were able to share fascinating stories and formulate intriguing hypotheses based on their observations.

These experiences highlighted the crucial role of domain expertise in uncovering the latent narratives embedded within the data and its visual representations. The input from specialists like musicologists and instrument makers proved indispensable in interpreting these stories accurately. Recognizing the value of these narratives, the development of a tool that facilitates the saving and interactive presentation of these stories emerged as a promising approach to making this wealth of knowledge accessible to a wider audience.

In the field of *MusEcology*, the domain experts, demonstrated a rapid comprehension of visualization techniques and the art of storytelling, bringing an extensive array of domain-specific knowledge to the table. This proficiency was not only evident in *MusEcology*but also became apparent through the various use cases within *InTaVia*. These instances underscored the necessity of possessing a broad spectrum of knowledge, skills, and creativity, along with a significant investment of time, to craft stories that are both entertaining and informative. This challenge is compounded by the need for a deep understanding of visualizations and their interplay, as well as a solid background in technical and data science aspects. The difficulty is further exacerbated by the lack of systematic availability of detailed information, such as event specifics, which requires manual curation.

Furthermore, it seems so important to focus on specific and smaller data subsets to enable concise and understandable stories. On the other hand, storytelling goes beyond picking characters and interesting stories. It has the power to represent larger communities and bring attention to exceptional cases. However, it's important not to impose patterns or trends on the data when they don't naturally occur. Doing so can oversimplify complex information, turning it into just numbers and making us forget its true value and delicate nature. Therefore, when it comes to telling stories through visualizations, it's crucial to find a balance and explain data biases, transformations and uncertainties (during the story). This means respecting the depth and detail of the data while also crafting stories that resonate and connect with people.

6.3 Stories of Intangible and Natural Heritage:

Throughout the Sustainability of Materials used for Musical Instruments 4, we delve into the intricate relationship between the diversity and harmony of musical instruments and their underlying connection to the variety and balance of species and ecosystems. This method accommodates not only the diverse, sometimes contradictory, requirements and interests, including those of adverse lobbies. These connections underscore as well the importance of biodiversity, highlighting the existence of countless unknown variants, modifications, and mutations, making every species and even every exicat significant. This notion echoes the practices observed in natural history museums, where extensive collections of species are preserved to maximize the gene pool [402]. Such practices suggest that the principles of preservation are equally vital for maintaining or restoring harmony in traditions and cultural values.

The interplay between actions within one dimension and reactions in others illustrates the systems' inherent desire for harmony. This is further emphasized in the conversation about preserving traditions and cultures, many of which we may not even be fully aware of, on platforms designed to amalgamate and host diverse inputs.

The concept of intangible heritage, encompassing cultural practices, alongside natural heritage, plays a significant role in colonial history, often driving the acquisition of "resources", including cultural heritage objects and traditions. Despite being alive—like animals, plants, ecosystems, and traditions—these entities are sometimes treated as mere objects. The ensuing challenges related to threats, preservation, and diversity, along with their consequences, are profoundly complex. Exemplary outlook to VBS on natural heritage give scrollytelling examples, including the narrative on gold[2] and its various uses in industries and culture, including fashion, or the challenges faced by the Mount Everest[3] attracting numerous visitors.

Ultimately, storytelling, particularly through visualization, emerges as a powerful method for effectively communicating complex socio-cultural-natural interdependent systems to policymakers, decision-makers, and a broader public audience, not only enhancing understanding but also fostering appreciation for the intricate relationships that define our world.

6.4 Digitization and Accessibility

The advent of digital collections transcends simple access, particularly highlighted during crisis such as the COVID-19 pandemic. Museums, often impacted by such emergencies, have the opportunity to adopt innovative digital strategies for a multitude of advantages. Implementing virtual tours led by professional guides and creating online catalogs that reflect the content of physical exhibits present significant possibilities such as the augmentation by contextualizing visualizations [140, 300]. The process of digitizing collections not only improves worldwide access but also encourages the exploration and connection among varied artifacts and throughout different collections [170].

This blend of access and interaction ignites creativity, innovation, and reveals previously hidden stories within museum collections. However, this leads to a dilemma: the rationale behind investing in virtual museums and contemporary media archives, which are inherently transient and prone to becoming outdated. The conversation surrounding the conservation of contemporary-media art highlights this issue, proposing potential solutions to address its impermanence. The argument regarding the durability of materials versus the staying power of digital representations merges with the realm of art, obscuring the distinction between what is permanent and what is fleeting.

[2] https://golden10.infografika.agency
[3] https://www.washingtonpost.com/graphics/world/scaling-everest

Historical practices, rather than guaranteeing longevity, are seen as evolving narratives that acknowledge the transient nature of their subjects. Within the confines of museums, artifacts like ancient jewelry and holy relics offer silent narratives, their meanings often obscured to modern interpretations. The question arises: how do these ancient objects interact with contemporary artistic expression, making them accessible to current audiences? The quest for meaning, buried under multiple layers of interpretation, remains challenging for both historians and artists to decipher.

6.5 Musical Instruments

Musical instruments are special creations that combine appearance and purpose, reflecting centuries of craftsmanship and cultural significance. These artifacts are difficult to classify simply because they embody both physical and sound aspects, and connect the people playing them with those listening. However, museums often find it hard to fully capture and share the essence of musical instruments, leaving visitors wanting a more engaging experience. Unlike stationary objects, musical instruments create feelings through sounds that can't be seen or touched, which is hard for traditional museum exhibits to showcase. Allowing visitors to play the instruments could offer a closer feel to their true sound, but this poses a risk to preserving the instruments' condition.

Museums are looking for new ways to let people interact with these objects without harming them. Modern technologies like 3D scanning, computed tomography, as well as 3D visualizations and virtual or augmented reality are showing great promise.

6.6 Scale and Scalability

Effective visualizations must be scalable, i.e. capable of depicting a range from individual to multiple entities and thereby supporting different levels of distant reading. This involves not only the capacity to handle vast amounts of data but also to contextualize various classes of entities within a unified framework. Such designs should enable users to engage in both overarching analyses and detailed explorations of close reading. The visualization of historical data is often challenged by its sheer volume and the inherent uncertainties, such as skewed distributions due to specific events or the ambiguity in the dating of objects [224]. These aspects demand visualization strategies that can represent significant occurrences without overwhelming the user, thus facilitating an accurate interpretation of historical narratives. Linking multiple views and employing interactive storytelling techniques can offer a more comprehensive understanding of the data, guiding users through analyses of complex or contested (hi)stories. To help users process large amounts of data visually, innovative interaction mechanisms have been developed that enable the display of additional information without causing visual clutter, utilizing techniques like fisheye views and semantic zooms to focus on relevant data subsets. Furthermore, to manage the complexity and scale of data, effective aggregation and summarization techniques are essential. This might involve the use of charts, treemaps, or other visual summarization tools that can present data in an accessible and interpretable format. One feasible use case is the visualization of overviews of whole databases or the resulting list during interactive searches [222]. Unfortunately, in case of the *InTaVia* knowledge graph, the sheer data volume led to overwhelmingly large datasets and respectively long loading times, so that overview visualizations only were possible via preprocessed aggregations. On the other hand, datasets in DH and CH are still often suffering from sparsity and data skew, so that interesting details are missing and visualization ideas have to be adjusted. The requirements depend on the expertise and interest of each user, which are highly diverse in a CH setting. Addressing these diverse needs of users involves allowing for customization and interactive engagement. This can be achieved among others through the integration of LLMs and AI to tailor visualizations based on user preferences and prior knowledge. By involving the user in the visualization process, systems can offer more meaningful and personalized insights.

6.7 Simplification & Sensitivity

As a computer scientist working with data from diverse domains, I understand the risks involved in digitizing cultural and artistic works. Transforming these artifacts into data can lead to a disconnection, where valuable pieces are perceived merely as numbers rather than meaningful expressions of creativity, especially with the focus on generalization of visualization systems. This shift underscores the importance of collaboration between researchers, domain experts, artists, and practitioners. By engaging with these stakeholders, we can gain insights that enrich our understanding and approach to working with data.

The challenge then becomes designing visualizations and systems that are not only functional but also culturally sensitive. We must question how our methodologies can be refined to respect the depth and context of the data we handle. One avenue could be VBS, allowing to contextualize data, presenting it within a broader narrative that can facilitate a more nuanced communication of results.

The journey from cultural artifacts to data and algorithms is fraught with potential for obscuring the ongoing transformations that underpin our visualizations. This is particularly pertinent in scenarios where visualizations are employed rhetorically, pre-loaded with interpretations that could diminish transparency.

This brings to light the critical issues of ownership and consent, reinforcing the need for mindful technology use, especially in contexts where sensitivity is paramount. Our goal should be to mitigate the risk of transitioning towards Electronic Colonialism [265], ensuring that our advancements in digitization and visualization strengthen rather than diminish the connection to the cultural and artistic heritage we aim to preserve and understand.

6.8 Changing Environment and Heritage

For me it is truly fascinating how diverse entities and their individual instances don't exist in a vacuum, but are in constant change and transaction with other entities. This dynamic interaction means that persons or objects can either ignite new ideas or, conversely, conflicts can emerge that threaten to 'destroy' them. This interplay underscores the fluidity and interconnectedness of various elements in our world.

In the realm of digital humanities, it's paramount to understand that the goal is not to supplant traditional methodologies. Instead, digital humanities seek to augment the conventional approaches by leveraging computational power. This integration not only enhances existing practices but also introduces novel methodologies to the field. Through the development of data models, databases, visualization tools, and other advancements, we are laying the groundwork for a more systematic and holistic approach to digitization and preservation. This process inherently allows for ongoing change and evolution, acknowledging that our understanding and interpretations are always in transition.

The field is characterized by continual transformation, spurred by reiterations, additions, and fresh interpretations.

Furthermore, according to Schmiedl and Klepacki the notion that intangible cultural heritage can remain static is a misconception [382]. Intangible cultural heritage is perpetually evolving, shaped by new interpretations, additions, and even external factors such as political conflicts. The stories behind these shifts bring to light the 'hidden destinies' of cultural heritage. I remember for instance, how Prof. Focht at the Musical Instrument Museums told me the story of the e-string, the highest and smallest string of violins. The strings were made of sheep guts, with the finest materials sourced from Italy. But the advent of the First World War led to a scarcity of high-quality gut strings. This scarcity prompted a shift to steel strings, which provided *almost* the same sound quality but with greater reliability [84]. This adaptation marks a significant change in the violin's history, symbolizing how external circumstances can catalyze enduring transformations in our cultural heritage. These stories remind us that change is the only constant, paving the way for new narratives to emerge from curiosity.

6.9 Conclusion

This dissertation represents an advancement in the fields of digital humanities and cultural heritage, highlighting the pivotal role of visualization-based storytelling in enhancing the comprehension and appreciation of complex cultural narratives. Through a meticulous examination of the integration between data visualization, narrative techniques, and user-centered design, this work underscores the transformative potential of digital technologies in the storytelling landscape.

Central to this thesis is the development of innovative visual analytics tools tailored for the exploration and presentation of cultural data. These tools are not only instrumental in bridging the gap between abstract data and tangible narratives but also facilitate a deeper engagement with cultural heritage through interactive and immersive storytelling practices. By focusing on diverse case studies, including the intricate narratives of musical instruments and their ecosystems, as well as the broader dimensions of European cultural heritage, this research underscores the versatility and impact of visualization-based storytelling across various domains.

A key contribution of this work lies in its holistic approach to the challenges inherent in digital humanities and cultural heritage. By leveraging the synergies between technological innovation and traditional storytelling, the thesis presents a comprehensive platform that supports the analysis, curation, and dissemination of cultural data. This approach not only enhances accessibility and engagement for a wide range of audiences but also fosters a richer appreciation and understanding of cultural heritage.

Moreover, this research sheds light on the importance of interdisciplinary collaboration, bringing together experts from diverse fields to enrich the storytelling process. This collaborative effort is crucial in navigating the complexities of cultural data, ensuring that the visualizations are both accurate and compelling.

In conclusion, this thesis not only contributes valuable insights and methodologies to the fields of digital humanities and cultural heritage but also opens new avenues for future research, paving the way for a deeper and more nuanced understanding of cultural heritage in the digital age.

Acronyms

3D	Three-Dimensional
AI	Artificial Intelligence
AR	Augmented Reality
BGCI	Botanic Gardens Conservation International's
CH	Cultural Heritage
CITES	Convention On International Trade In Endangered Species Of Wild Fauna And Flora
DCL	Data Curation Lab
DH	Digital Humanities
GLAM	Galleries, Libraries, Archives And Museums
HTML	Hypertext Markup Language
IKG	InTaVia Knowledge Graph
IUCN	International Union For Conservation Of Nature
JSON	JavaScript Object Notation
LLMs	Large Language Models
ST	Storytelling Suite
VA studio	Visual Analytics Studio
VBS	Visualization-Based Storytelling
VR	Virtual Reality
XR	Mixed Reality

Bibliography

1. A. Abbott. "Humanity's cultural history captured in 5-minute film". *Nature*, 2014.
2. H. P. Abbott. "The evolutionary origins of the storied mind: Modeling the prehistory of narrative consciousness and its discontents". *Narrative* 8:3, 2000, pp. 247–256.
3. M. Abet, N. K. B. Khalid, et al. "Enhancing Undergraduate Student's Understanding of Cultural Heritage Studies Through Digital Storytelling Software". *Malaysian Journal of Social Sciences and Humanities (MJSSH)* 7:3, 2022, e001362–e001362.
4. W. Aigner, S. Miksch, H. Schumann, and C. Tominski. *Visualization of time-oriented data*. Vol. 1. Springer.
5. B. Alsallakh, L. Micallef, W. Aigner, H. Hauser, S. Miksch, and P. Rodgers. "The state-of-the-art of set visualization". In: *Computer Graphics Forum*. Vol. 35. 1. Wiley Online Library. 2016, pp. 234–260.
6. F. Amini, N. Henry Riche, B. Lee, C. Hurter, and P. Irani. "Understanding Data Videos: Looking at Narrative Visualization through the Cinematography Lens". In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Association for Computing Machinery, Seoul, Republic of Korea, 2015, pp. 1459–1468. ISBN: 9781450331456. DOI: 10.1145/2702123.2702431.
7. P. André, M. L. Wilson, A. Russell, D. A. Smith, A. Owens, and M. Schraefel. "Continuum: designing timelines for hierarchies, relationships and scale". In: *Proceedings of the 20th annual ACM symposium on User interface software and technology*. 2007, pp. 101–110.
8. C. Andrews, A. Endert, B. Yost, and C. North. "Information visualization on large, high-resolution displays: Issues, challenges, and opportunities". English. *Information visualization* 10:4, 2011, pp. 341–355.
9. N. Andrienko and G. Andrienko. "A Framework for Using Coordinated Displays for the Analysis of Multidimensional, Spatial, and Temporal Data". In: *Geographic Hypermedia*. Springer, 2006, pp. 293–308.
10. V. Angyalossy, E. Amano, and E. S. Alves. "Madeiras utilizadas na fabricação de arcos para instrumentos de corda: aspectos anatômicos". *Acta Botanica Brasilica* 19:4, 2005, pp. 819–834. URL: http://www.scielo.br/pdf/abb/v19n4/a18v19n4.pdf.
11. Y. Annanias, D. Zeckzer, G. Scheuermann, and D. Wiegreffe. "An Interactive Decision Support System for Land Reuse Tasks". *IEEE Computer Graphics and Applications* 01, 2022, pp. 1–1. ISSN: 1558-1756. DOI: 10.1109/MCG.2022.3175604.
12. Anne Frank House. *Anne Frank: The Timeline*. URL: https://www.annefrank.org/en/anne-frank/the-timeline/. Accessed: 2024-02-27.

13. anon. *Major Battles in the Napoleonic Wars*. URL: http://timemapper.okfnlabs.org/anon/0s5rzt-major-battles-in-the-napoleonic-wars. Accessed: 2023-25-06.
14. N. Armitage. "The biographical network method". *Sociological Research Online* 21:2, 2016, pp. 165–179.
15. D. Arnold. "Computer graphics and cultural heritage: from one-way inspiration to symbiosis, part 1". *IEEE computer graphics and applications* 34:3, 2014, pp. 76–86.
16. T. Arnold and L. Tilton. *Distant Viewing: Computational Exploration of Digital Images*. MIT Press, 2023.
17. L. Artamoshkina, K. Morawski, and D. Prokudin. "Digital humanities and development of the biographical method". *Vestnik of Saint Petersburg University. Philosophy and Conflict Studies* 37, 2021, pp. 310–321. DOI: 10.21638/spbu17.2021.210.
18. Z. Aslan. *Forword of 'A Guide to Risk Management of Cultural Heritage'*. URL: https://www.iccrom.org/sites/default/files/Guide-to-Risk-Managment_English.pdf. Accessed: 2024-03-30.
19. B. Bach, P. Dragicevic, D. Archambault, C. Hurter, and S. Carpendale. "A descriptive framework for temporal data visualizations based on generalized space-time cubes". In: *Computer graphics forum*. Vol. 36. Wiley Online Library. 2017, pp. 36–61.
20. B. Bach, N. Kerracher, K. W. Hall, S. Carpendale, J. Kennedy, and N. Henry Riche. "Telling Stories about Dynamic Networks with Graph Comics". In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. Association for Computing Machinery, San Jose, California, USA, 2016, pp. 3670–3682. ISBN: 9781450333627. DOI: 10.1145/2858036.2858387. URL: https://doi.org/10.1145/2858036.2858387.
21. B. Bach, N. H. Riche, S. Carpendale, and H. Pfister. "The Emerging Genre of Data Comics". *IEEE Computer Graphics and Applications* 37:3, 2017, pp. 6–13. DOI: 10.1109/MCG.2017.33.
22. B. Bach, C. Shi, N. Heulot, T. Madhyastha, T. Grabowski, and P. Dragicevic. "Time Curves: Folding Time to Visualize Patterns of Temporal Evolution in Data". *IEEE Transactions on Visualization and Computer Graphics* 22:1, 2016, pp. 559–568. DOI: 10.1109/TVCG.2015.2467851.
23. B. Bach, Z. Wang, M. Farinella, D. Murray-Rust, and N. Henry Riche. "Design Patterns for Data Comics". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Association for Computing Machinery, Montreal QC, Canada, 2018, pp. 1–12. ISBN: 9781450356206. DOI: 10.1145/3173574.3173612.
24. S. Baelo-Allué and M. Calvo-Pascual. *Transhumanism and posthumanism in twenty-first century narrative*. Routledge, 2021.
25. C. Baracchini, M. Callieri, M. Corsini, M. Dellepiane, U. Dercks, D. Keultjes, C. Montani, M. Scognamiglio, R. Scopigno, R. Sigismondi, et al. "Starting the cenobium project: The cloister of monreale (sicily) revealed". *Proceedings of VAST 2006*, 2006, pp. 100–110.
26. V. Bartalesi, G. Coro, E. Lenzi, P. Pagano, and N. Pratelli. "From unstructured texts to semantic story maps". *International Journal of Digital Earth* 16:1, 2023, pp. 234–250.

27. V. Barve and J. Otegui. "bdvis: visualizing biodiversity data in R". *Bioinformatics* 32:19, 2016, pp. 3049–3050.
28. L. Bedford. "Storytelling: The real work of museums". *Curator: the museum journal* 44:1, 2001, pp. 27–34.
29. B. C. Bennett. "The Sound of Trees: Wood Selection in Guitars and Other Chordophones". *Economic Botany* 70:1, 2016, pp. 49–63. ISSN: 0013-0001. DOI: 10.1007/s12231-016-9336-0.
30. Á. Bernád, M. Kaiser, K. Lejtovicz, and M. Schlögl. "Mapping historical networks. Working with biographical data". In: *Entangled Worlds: Network analysis and complexity theory in historical and archeological research*. 2017.
31. Á. Z. Bernád and M. Kaiser. "The biographical formula: Types and dimensions of biographical networks". In: *Proceedings of the Second Conference on Biographical Data in a Digital World 2017*. 2017, pp. 45–52.
32. F. Berthaut, M. Marshall, S. Subramanian, and M. Hachet. "Rouages: Revealing the mechanisms of digital musical instruments to the audience". In: *NIME: Proceedings of the International Conference on New Interfaces for Musical Expression (pp. 165-169)*. 2013.
33. A. Betti, T. Castermans, B. Speckmann, H. Van Den Berg, and K. Verbeek. "GlamMapping trove". In: *VALA2016*. 2016.
34. P. Beytía and J. Schobin. "Networked Pantheon: a Relational Database of Globally Famous People". *Available at SSRN 3255401*, 2018.
35. Black Liberation 1969 Archive. *January 1969: Mapping the Sit-in*. URL: https://blacklib1969.swarthmore.edu/neatline/fullscreen/sit-in-map. Accessed: 2023-25-06.
36. K. Blumenstein. "Interweaving Physical Artifacts with Visualization on Digital Media in Museums". In: *Proceedings of the 2018 ACM Companion International Conference on Interactive Surfaces and Spaces*. ISS '18 Companion. Association for Computing Machinery, Tokyo, Japan, 2018, pp. 1–6. ISBN: 9781450360104. DOI: 10.1145/3280295.3280297.
37. D. Boje and N. Tourani. "The agential materiality of storytelling". *Qualitative Methodologies in Organization Studies: Volume I: Theories and New Approaches*, 2018, pp. 113–135.
38. H. Bolin. "The Re-generation of Mythical Messages. Rock Art and Storytelling in Northern Fennoscandia". *Fennoscandia archaeologica* XXVII, 2010.
39. T. Borman and B. Stoel. "Review of the Uses of Computed Tomography for Analyzing Instruments of the Violin Family with a Focus on the Future". *J Violin Soc Am: VSA Papers* 22:1, 2009, pp. 1–12.
40. M. Bostock, V. Ogievetsky, and J. Heer. "D³ Data-Driven Documents". *IEEE Transactions on Visualization and Computer Graphics* 17:12, 2011, pp. 2301–2309. DOI: 10.1109/TVCG.2011.185.
41. Botanic Gardens Conservation International. *Botanic Gardens Conservation International GlobalTreeSearch*. (Retrieved 2022-03-31). 2022.

42. Botanic Gardens Conservation International. *Botanic Gardens Conservation International GlobalTreeSearch*. (Retrieved 2022-03-31). 2022.

43. A. Bouënard, S. Gibet, and M. M. Wanderley. "Enhancing the visualization of percussion gestures by virtual character animation". In: *NIME*. 2008, pp. 38–43.

44. L. Bounegru, T. Venturini, J. Gray, and M. Jacomy. "Narrating networks: Exploring the affordances of networks as storytelling devices in journalism". *Digital Journalism* 5:6, 2017, pp. 699–730.

45. S. ter Braake, A. Fokkens, R. Sluijter, P. Arthur, and E. Wandl-Vogt. "Biographical Data in a Digital World 2017: Proceedings of the Second Conference on Biographical Data in a Digital World 2017 (BD 2017)". In: *Wokshop Proceedings*. Vol. 2119. CEUR-WS. org, 2017.

46. S. ter Braake, A. Fokkens, R. Sluijter, T. Declerck, and E. Wandl-Vogt. "Biographical Data in a Digital World 2015: Proceedings of the First Conference on Biographical Data in a Digital World 2015 (BD 2015), Amsterdam, The Netherlands, April 9, 2015." In: *Workshop proceedings*. Vol. 1399. CEUR-WS. org. 2015.

47. A. J. Bradley, M. El-Assady, K. Coles, E. Alexander, M. Chen, C. Collins, S. Jänicke, and D. J. Wrisley. "Visualization and the digital humanities". *IEEE computer graphics and applications* 38:6, 2018, pp. 26–38.

48. M. Brehmer, B. Lee, B. Bach, N. H. Riche, and T. Munzner. "Timelines revisited: A design space and considerations for expressive storytelling". *IEEE transactions on visualization and computer graphics* 23:9, 2016. ISBN: 1077-2626 Publisher: IEEE, pp. 2151–2164.

49. M. Brehmer, B. Lee, N. Henry Riche, D. Tittsworth, K. Lytvynets, D. Edge, and C. White. "Timeline Storyteller: The Design & Deployment of an Interactive Authoring Tool for Expressive Timeline Narratives". In: *Computation+Journalism Symposium*. 2019, pp. 1–5. URL: https://www.microsoft.com/en-us/research/publication/timeline-storyteller-the-design-deployment-of-an-interactive-authoring-tool-for-expressive-timeline-narratives/.

50. I. Brémaud and N. Poidevin. "Approches culturelles et mecaniques dans le choix des bois en facture: cas des archets anciens: Cultural and mechanical approaches in the choice of woods in instrument making : the case of early bows". Collection Pensée Musicale, 2013. Ed. by M. Castellengo and H. Genevois, pp. 1–27.

51. I. Brémaud, B. Thibaut, and K. Minato. "A database linking woody species, vibrational properties, and uses in musical instruments of the world". In: *Proceedings of International Symposium on Musical Acoustics 2007*. Ed. by J. Agullo and A. Barjau (eds). OK Punt Publications, Barcelona, Spain, 2007. ISBN: 978-84-934142-1-4. URL: https://hal.archives-ouvertes.fr/hal-01979437.

52. P. Bridgewater, S. Arico, and J. Scott. "Biological Diversity and Cultural Diversity: The Heritage of Nature and Culture through the Looking Glass of Multilateral Agreements". *International Journal of Heritage Studies* 13:4-5, 2007, pp. 405–419. ISSN: 1352-7258. DOI: 10.1080/13527250701351130.

53. Brown, Vincent. *Slave Revolt in Jamaica, 1760-1761: A Cartographic Narrative*. URL: http://revolt.axismaps.com/map/. Accessed: 2023-25-06.

54. J. Bruner. "Chapter VI: Narrative and Paradigmatic Modes of Thought". *Teachers College Record* 86:6, 1985, pp. 97–115. DOI: 10.1177/016146818508600606.

55. G. Bruseker, N. Carboni, and A. Guillem. "Cultural heritage data management: The role of formal ontology and CIDOC CRM". *Heritage and archaeology in the digital age: acquisition, curation, and dissemination of spatial cultural heritage data*, 2017, pp. 93–131.

56. V. Bucur. *Acoustics of wood*. 2nd ed. Vol. 1431-8563. Springer series in wood science. Springer, Berlin and New York, 2006.

57. V. Bucur. *Handbook of Materials for String Musical Instruments*. Springer International Publishing, Cham, 2016. ISBN: 978-3-319-32080-9. DOI: 10.1007/978-3-319-32080-9.

58. V. Bucur. *Handbook of Materials for Wind Musical Instruments*. Springer International Publishing, Cham, 2019. DOI: 10.1007/978-3-030-19175-7.

59. E. Bunout. "Visualisation of the prosopography of Polish and German experts on Eastern Europe: Are non-computed data useable for visualisation?" In: *DH Benelux conference 2016*. 2016.

60. R. Busselle and H. Bilandzic. "Fictionality and Perceived Realism in Experiencing Stories: A Model of Narrative Comprehension and Engagement". *Communication Theory* 18:2, 2008, pp. 255–280. DOI: 10.1111/j.1468-2885.2008.00322.x.

61. J. Campbell. *The Hero with a Thousand Faces*. Vol. 17. New World Library, 2008.

62. S. K. Card, J. Mackinlay, and B. Shneiderman. *Readings in information visualization: using vision to think*. Morgan Kaufmann, 1999.

63. D. Ceneda, T. Gschwandtner, T. May, S. Miksch, H.-J. Schulz, M. Streit, and C. Tominski. "Characterizing Guidance in Visual Analytics". English. *IEEE Transactions on Visualization and Computer Graphics* 23:1, 2017, pp. 111–120. ISSN: 1077-2626. DOI: 10.1109/TVCG.2016.2598468.

64. W. C. M. Centre, C. on International Trade in Endangered Species of Wild Fauna, and Flora. *Checklist of CITES species: a reference to the appendices to the Convention on international trade in endangered species of wild fauna and flora*. United Nations Publications, 2001.

65. M. Champagne. "Diagrams of the past: How timelines can aid the growth of historical knowledge". *Cognitive Semiotics* 9:1, 2016, pp. 11–44.

66. E. M. Champion. "Digital humanities is text heavy, visualization light, and simulation poor". *Digital Scholarship in the Humanities* 32:suppl_1, 2017, pp. i25–i32.

67. A. T. Chen, J. Martell, and P. Lach. "Supporting discovery through contextual representation: developing a tool for visually exploring slave narratives". In: *2016 Workshop on Visualization for the Digital Humanities, Co-located with IEEE VIS*. 2016.

68. V. Ciorna, N. Médoc, G. Melançon, F. Petry, and M. Ghoniem. "A tour through the zoo of scented widgets". In: *25th EuroGraphics Conference on Visualization*. Eurographics-The European Association for Computer Graphic. 2023.

69. L. Ciotoli, M. Alinam, and I. Torre. "Sail with Columbus: Navigation through Tangible and Interactive Storytelling". In: *CHItaly 2021: 14th Biannual Conference of the Italian SIGCHI Chapter*. 2021, pp. 1–6.

70. CITES. *CITES CoP19 Committee I - 17 November 2022 - Evening session (English)*. [Online; accessed 5-May-2023]. 2022. URL: https://www.youtube.com/live/TBIJ0zGiryk.

71. F. Clarizia, F. Colace, M. De Santo, A. Lorusso, F. Marongiu, and D. Santaniello. "Augmented Reality and Gamification technics for visit enhancement in archaeological parks". In: *2022 IEEE 2nd IoT Vertical and Topical Summit for Tourism (IoTT)*. IEEE. 2022, pp. 1–4.

72. N. Cohn. "Visual Narrative Structure". *Cognitive Science* 37:3, 2013, pp. 413–452. DOI: 10.1111/cogs.12016.

73. M. Conlen, M. Vo, A. Tan, and J. Heer. "Idyll Studio: A Structured Editor for Authoring Interactive & Data-Driven Articles". In: *ACM User Interface Software & Technology (UIST)*. 2021. DOI: 10.1145/3472749.3474731.

74. Convention on International Trade in Endangered Species of Wild Fauna and Flora. *Convention on International Trade in Endangered Species of Wild Fauna and Flora Speciesplus*.

75. J. Cranston. *Mapping Titian*. URL: http://www.mappingtitian.org/. Accessed: 2021-09-04.

76. L. Cron. *Wired for story: The writer's guide to using brain science to hook readers from the very first sentence*. Ten Speed Press, 2012.

77. P. Cruz and P. Machado. "Generative Storytelling for Information Visualization". *IEEE Computer Graphics and Applications* 31:2, 2011, pp. 80–85. DOI: 10.1109/MCG.2011.23.

78. C. D'Ignazio and L. F. Klein. "Feminist Data Visualization". In: *IEEE VIS 2016, Workshop on Visualization for the Digital Humanities , VIS4DH@VIS2016*. Baltimore, Maryland, USA, 2016. URL: https://vis4dh.dbvis.de/papers/2016/Feminist%5C%20Data%5C%20Visualization.pdf.

79. D3. *The JavaScript library for bespoke data visualization*. https://d3js.org/. [accessed 10-July-2023].

80. D3.js. *D3.js*. (Retrieved 2022-03-31). 2022.

81. F. Dal Falco and S. Vassos. "Museum experience design: A modern storytelling methodology". *The Design Journal* 20:sup1, 2017, S3975–S3983.

82. Dance, Gabriel and Goodridge, Elisabeth. *The Family Tree of Michelle Obama, the First Lady*. URL: https://archive.nytimes.com/www.nytimes.com/interactive/2009/10/08/us/politics/20091008-obama-family-tree.html. Accessed: 2024-02-27.

83. M. Daniels. *The Largest Vocabulary in Hip Hop*. https://pudding.cool/projects/vocabulary/ (Accessed 2019-06-24). 2014.

84. E. Dann. "The Second Revolution in the History of the Violin: A Twentieth-Century Phenomenon". *College Music Symposium* 17:2, 1977, pp. 64–71. ISSN: 00695696, 2334203X. URL: http://www.jstor.org/stable/40373889 (visited on 03/31/2024).

85. DARIAH-DE. *DARIAH-DE Geo-Browser*. URL: https://geobrowser.de.dariah.eu. Accessed: 2024-02-27.

86. E. Davis and B. Heravi. "Linked data and cultural heritage: a systematic review of participation, collaboration, and motivation". *Journal on Computing and Cultural Heritage (JOCCH)* 14:2, 2021, pp. 1–18.

87. S. B. Davis, E. Bevan, and A. Kudikov. "Just in time: defining historical chronographics". In: *Electronic Visualisation in Arts and Culture*. Springer, 2013, pp. 243–257.

88. K. Dawe. "The cultural study of musical instruments". In: *The Cultural Study of Music*. Routledge, 2012, pp. 217–227.

89. A. Daza, A. Fokkens, R. Hadden, E. Hyvönen, M. Koho, and E. Wandl-Vogt. "Biographical Data in a Digital World 2022 (BD 2022) Workshop". In: *Digital Humanities 2022*. The Alliance of Digital Humanities Organizations (ADHO), 2022.

90. A. Daza, A. Fokkens, P. Osenova, K. Simov, A. Popov, P. Arthur, T. Declerck, R. Sluijter, S. ter Braake, and E. Wandl-Vogt. "Editorial Introduction to Biographical Data in a Digital World 2019 (BD 2019)". *Wokshop Proceedings*, 2019.

91. V. De Boer, J. Wielemaker, J. Van Gent, M. Hildebrand, A. Isaac, J. Van Ossenbruggen, and G. Schreiber. "Supporting linked data production for cultural heritage institutes: the amsterdam museum case study". In: *The Semantic Web: Research and Applications: 9th Extended Semantic Web Conference, ESWC 2012, Heraklion, Crete, Greece, May 27-31, 2012. Proceedings 9*. Springer. 2012, pp. 733–747.

92. A. De Fina. "Storytelling and audience reactions in social media". *Language in Society* 45:4, 2016, pp. 473–498.

93. M. De'Gennaro, C. Colella, A. Langella, P. Cappelletti, et al. "Decay of Campanian ignimbrite stoneworks in some monuments of the Caserta area". *Science and technology for cultural heritage* 4, 1995, pp. 75–86.

94. *Definition of the CIDOC Conceptual Reference Model*. Technical report. Version 7.2. CIDOC CRM Special Interest Group, 2021.

95. M. Denil. "Storied Maps". *Cartographic Perspectives* 84, 2017, pp. 5–22. DOI: 10.14714/CP84.1374.

96. E. Dinerstein et al. "An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm". *BioScience* 67:6, 2017, pp. 534–545. ISSN: 0036-8075. DOI: 10.1093/biosci/bix014.

97. M. Doerr, S. Gradmann, S. Hennicke, A. Isaac, C. Meghini, and H. Van de Sompel. "The europeana data model (edm)". In: *World Library and Information Congress: 76th IFLA general conference and assembly*. Vol. 10. IFLA. 2010, p. 15.

98. E. I. Dolan. "Review: MIMO: Musical Instrument Museums Online". *Journal of the American Musicological Society* 70:2, 2017, pp. 555–565. ISSN: 0003-0139. DOI: 10.1525/jams.2017.70.2.555. URL: https://doi.org/10.1525/jams.2017.70.2.555.

99. Donina, Daria And Fekhretdinov, Timur And Vakhitova, Sabina And Nedkova, Kristina And Starkov, Andrei And Aghion, Philip And Zotova, Anastasia And Mizinov, Anton (TASS). *Mercator: It's a flat, flat world!* URL: https://mercator.tass.com/. Accessed: 2023-25-06.

100. M. Dörk, S. Carpendale, and C. Williamson. "The information flaneur: A fresh look at information seeking". In: *Proceedings of the SIGCHI conference on human factors in computing systems*. 2011, pp. 1215–1224.

101. M. Dörk, P. Feng, C. Collins, and S. Carpendale. "Critical InfoVis: Exploring the Politics of Visualization". In: *CHI '13 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '13. Association for Computing Machinery, Paris, France, 2013, pp. 2189–2198. ISBN: 9781450319522. DOI: 10.1145/2468356.2468739.

102. J. Drucker. *The digital humanities coursebook: an introduction to digital methods for research and scholarship*. Routledge, 2021.

103. N. Duarte. *Resonate: Present Visual Stories that Transform Audiences*. John Wiley & Sons, 2010.

104. G. Dullat. *Holzblasinstrumentenbau: Entwicklungsstufen und Technologien*. 1. Aufl. Vol. 4040. Edition Moeck. Moeck, Celle, 1990. ISBN: 3-87549-032-0.

105. B. Dykes. *Effective data storytelling: how to drive change with data, narrative and visuals*. John Wiley & Sons, 2019.

106. C. Ebel, J. Tuominen, M. Schlögl, K. Joonas, and F. Windhager. *InTaVia Data Model (IDM-RDF)*. URL: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5e67fcfb6&appId=PPGMS. Deliverable within the H2020 project InTaVia. 2021.

107. R. Eccles, T. Kapler, R. Harper, and W. Wright. "Stories in geotime". *Information Visualization* 7:1, 2008, pp. 3–17.

108. Ø. Eide, A. Felicetti, C. Ore, A. D'Andrea, and J. Holmen. "Encoding cultural heritage information for the semantic web. Procedures for data integration through CIDOC-CRM mapping". In: *Open Digital Cultural Heritage Systems Conference*. Vol. 25. 2008, p. 47.

109. P. Elsasser, G. Koch, and S. Björn. *Sind Musikinstrumente umweltschädlich? Eine Abschätzung der deutschen Importe an (Tropen-) Hölzern durch den Import von Musikinstrumenten*. Technical report. Hamburg, 2011, p. 19.

110. Emotive. *Emotive - Storytelling for Cultural Ceritage*. URL: https://emotiveproject.eu. Accessed: 2023-01-03.

111. L. Ernoul, A. Wardell-Johnson, L. Willm, A. Béchet, O. Boutron, R. Mathevet, S. Arnassant, and A. Sandoz. "Participatory mapping: Exploring landscape values associated with an iconic species". *Applied Geography* 95, 2018, pp. 71–78.

112. Esri. *An Infamous Day*. URL: http://storymaps.esri.com/stories/2016/pearl-harbor/index.html. Accessed: 2021-09-04.

113. Esri. *ArcGIS Story Maps*. URL: https://storymaps.arcgis.com/. Accessed: 2023-06-02.

114. Esri. *Justice deferred - Executive Order 9066 and the geography of Japanese American imprisonment*. URL: https://storymaps.arcgis.com/stories/6538609586d34405a1d3cd24098519d3. Accessed: 2023-25-06.
115. Esri. *Rotterdam Buildings Built Before/After the War*. URL: https://www.arcgis.com/home/webmap/viewer.html?webmap=246f13706e39405bbc4317246aed43e7&extent=4.47,51.9162,4.5206,51.9327. Accessed: 2024-02-27.
116. Europeana. *MIMO and EDM*. URL: https://pro.europeana.eu/page/mimo-edm. Accessed: 2024-03-30.
117. F. Fabbri, F. Collina, S. Barzaghi, et al. "AI and chatbots as a storytelling tool to personalize the visitor experience. The case of National Museum of Ravenna". In: *ExICE23*. 2023. URL: https://spice-h2020.eu/conference/papers/posters/ExICE23_paper_8963.pdf.
118. M. J. Ferreira, R. B. Paradeda, R. Oliveira, V. Nisi, and A. Paiva. "Using Storytelling to Teach Children Biodiversity". In: *Interactive Storytelling: 15th International Conference on Interactive Digital Storytelling, ICIDS 2022, Santa Cruz, CA, USA, December 4–7, 2022, Proceedings*. Springer. 2022, pp. 3–27.
119. N. Ferreira, L. Lins, D. Fink, S. Kelling, C. Wood, J. Freire, and C. Silva. "Birdvis: Visualizing and understanding bird populations". *IEEE transactions on visualization and computer graphics* 17:12, 2011, pp. 2374–2383.
120. S. Few. *Tell Me a Story, or Not*. URL: https://www.perceptualedge.com/blog/?p=2568. Accessed: 2022-07-04. 2017.
121. N. H. Fletcher and T. D. Rossing. *The physics of musical instruments*. Springer Science & Business Media, 2012.
122. Flourish. *Flourish - Beautiful and easy data visualization and storytelling*. URL: https://flourish.studio/. Accessed: 2023-01-04.
123. Flow Immersive, Inc. *Flow Immersive - Build visually compelling data stories and live 3d data applications*. URL: https://flowimmersive.com/. Accessed: 2023-06-02.
124. Fluxguide. *Around the Globe with Reinhold Würth*. URL: https://www.youtube.com/watch?v=PdUhkXaIUfE. Accessed: 2023-25-06.
125. Fluxguide. *Around the Globe with Reinhold Würth - Würth Collection App*. https://youtu.be/jrleGuGus5I. 2020.
126. Fluxguide. *Kosmos Kaffee*. URL: https://www.youtube.com/watch?v=I1_wsFFy_3U. Accessed: 2023-25-06.
127. Fluxguide. *VIrtulleum - Stadtmuseum Tulln*. URL: https://youtu.be/nPvFvfXV8h0. Accessed: 2021-09-04.
128. Fluxguide Ausstellungssysteme GmbH. *Virtulleum*. URL: www.virtulleum.at. Accessed: 2023-25-06.
129. A. Fokkens, S. Ter Braake, N. Ockeloen, P. Vossen, S. Legêne, G. Schreiber, and V. de Boer. "BiographyNet: Extracting Relations Between People and Events". In: *Europa baut auf Biographien: Aspekte, Bausteine, Normen und Standards für eine europäische Biographik*. new academic press, 2017, pp. 193–227.

130. J. A. Foley et al. "Global consequences of land use". *Science (New York, N.Y.)* 309:5734, 2005, pp. 570–574. DOI: 10.1126/science.1111772.

131. F. Fontanella, F. Colace, M. Molinara, A. S. Di Freca, and F. Stanco. *Pattern recognition and artificial intelligence techniques for cultural heritage*. 2020.

132. M. Franke, M. Knabben, J. Lang, S. Koch, and T. Blascheck. "A Comparative Study of Visualizations for Multiple Time Series." In: *VISIGRAPP (3: IVAPP)*. 2022, pp. 103–112.

133. R. P. Franzosi. "Sociology, narrative, and the quality versus quantity debate (Goethe versus Newton): Can computer-assisted story grammars help us understand the rise of Italian fascism (1919–1922)?" *Theory and Society* 39, 2010, pp. 593–629.

134. G. Freytag. *Technique of the Drama: An Exposition of Dramatic Composition and Art*. University Press of the Pacific, 1863.

135. Gabrielle Ione Hickmon. *How You Play Spades is How You Play Life*. URL: https://pudding.cool/2021/08/spades/. Accessed: 2023-25-06.

136. L. Geerlings. "A Visual Analysis of Rosey E. Pool's Correspondence Archives. Biographical Data, Intersectionality, and Social Network Analysis." In: *BD*. 2015, pp. 61–67.

137. G. Genette. *Narrative Discourse: An Essay in Method*. Cornell University Press, 1983.

138. Georgia Humanities. *Southern Literary Trail*. URL: https://www.georgiahumanities.org/southern-literary-trail-story-map/. Accessed: 2021-09-04.

139. O. Gergaud, M. Laouenan, and E. Wasmer. "A Brief History of Human Time. Exploring a database of" notable people"". *LIEPP Working Paper* 46, 2016.

140. Germanisches National Museum. *Daily Life In The Middle Ages*. URL: https://alltagimmittelalter.gnm.de/. Accessed: 2023-25-06.

141. N. Gershon and W. Page. "What Storytelling Can Do for Information Visualization". *Commun. ACM* 44:8, 2001, pp. 31–37. ISSN: 0001-0782. DOI: 10.1145/381641.381653.

142. S. Ghani, N. Elmqvist, and D. S. Ebert. "MultiNode-Explorer: A Visual Analytics Framework for Generating Web-based Multimodal Graph Visualizations." In: *EuroVA@ EuroVis*. 2012.

143. Gianpaolo Coro. *The Giant Squid: When Myth Encounters Science*. URL: https://tool.dlnarratives.eu/storymaps/gianpaolo.51/N305/?visualization=map. Accessed: 2023-25-06.

144. Giorgia Lupi. *Visualizing Painters' Lives*. URL: http://giorgialupi.com/visualizing-painters-lives. Accessed: 2024-02-27.

145. B. Gixhari, S. Dias, B. Hodaj, H. Ismaili, and H. Vrapi. "Geo-information analysis of fruit trees species in Albania". *Poljoprivreda i Sumarstvo* 60:1, 2014, p. 63.

146. M. Gleicher. "Considerations for Visualizing Comparison". *IEEE Transactions on Visualization and Computer Graphics* 24:1, 2018, pp. 413–423. DOI: 10.1109/TVCG.2017.2744199.

147. K. Glinka, C. Pietsch, and M. Dörk. "Past Visions and Reconciling Views: Visualizing Time, Texture and Themes in Cultural Collections." *DHQ: Digital Humanities Quarterly* 2, 2017.

148. Global Biodiversity Information Facility. *Global Biodiversity Information Facility*. en. https://www.gbif.org. (Retrieved 2022-03-31). 2022.

149. T. Gonçalves, A. P. Afonso, and B. Martins. "Cartographic visualization of human trajectory data: Overview and analysis". *Journal of Location Based Services* 9:2, 2015, pp. 138–166.

150. Google Cloud. *Looker - Your unified business intelligence platform. Self-service. Governed. Embedded.* URL: https://cloud.google.com/looker. Accessed: 2023-06-02.

151. C. Gosden and Y. Marshall. "The cultural biography of objects". *World archaeology* 31:2, 1999, pp. 169–178.

152. J. Gottschall. *The storytelling animal: How stories make us human*. Houghton Mifflin Harcourt, 2012.

153. A. Grebe. *Albrecht Dürer. Die Geschichte seines Ruhms*. Imhof Verlag, 2012.

154. A. Grebe. *Albrecht Dürer. Künstler, Werk und Zeit*. wbg Academic, 2013.

155. A. Grebe. *Dürer. Die Geschichte seines Ruhms*. Petersberg, 2013.

156. A. Grebe. *Dürer. Künstler, Werk und Zeit*. wbg Academic, 2013.

157. A. Grebe and G. U. Großmann. *Albrecht Dürer. Niederländische Reise. Tagebuch und Kommentar*. Imhof Verlag, 2013.

158. S. Hachmeyer. "The Archaeology of Musical Bamboos: Native Bamboos and Pre-Hispanic Flutes on the Andean Altiplano around Lake Titicaca (A First Approximation)". *Journal of Anthropological Archaeology* 68, 2022, p. 101462. ISSN: 02784165. DOI: 10.1016/j.jaa.2022.101462.

159. K. W. Hall, A. J. Bradley, U. Hinrichs, S. Huron, J. Wood, C. Collins, and S. Carpendale. "Design by Immersion: A Transdisciplinary Approach to Problem-Driven Visualizations". *IEEE transactions on visualization and computer graphics* 26:1, 2020, pp. 109–118. DOI: 10.1109/TVCG.2019.2934790.

160. N. Halloran. *The Fallen of World War II*. URL: http://www.fallen.io/ww2/. Accessed: 2022-10-07.

161. A. Harding. "Introduction: Biographies of Things". *Distant Worlds Journal* 1, 2016, pp. 5–10. DOI: 10.11588/dwj.2016.1.30158. URL: https://journals.ub.uni-heidelberg.de/index.php/dwj/article/view/30158.

162. M. Harrower and C. A. Brewer. "ColorBrewer.org: an online tool for selecting colour schemes for maps". *The Cartographic Journal* 40:1, 2003, pp. 27–37.

163. M. Harrower and C. A. Brewer. "ColorBrewer.org: An Online Tool for Selecting Colour Schemes for Maps". *The Cartographic Journal* 40:1, 2003, pp. 27–37. DOI: 10.1179/000870403235002042. eprint: https://www.tandfonline.com/doi/pdf/10.1179/000870403235002042. URL: https://www.tandfonline.com/doi/abs/10.1179/000870403235002042.

164. S. Havre, E. Hetzler, P. Whitney, and L. Nowell. “Themeriver: Visualizing thematic changes in large document collections”. *IEEE transactions on visualization and computer graphics* 8:1, 2002, pp. 9–20.

165. HCA, Heritage Crafts Association. “Red List of Endangered Crafts”. *The Heritage Crafts Association*, 2021. URL: https://heritagecrafts.org.uk/wp-content/uploads/2021/05/HCA-Red-List-2021-leaflet-optimised.pdf.

166. Y. He, S. Cao, Y. Shi, Q. Chen, K. Xu, and N. Cao. “Leveraging Large Models for Crafting Narrative Visualization: A Survey”. *arXiv preprint arXiv:2401.14010*, 2024.

167. K. Head. “Gravity for beginners”. *University of British Columbia* 2053, 2003.

168. J. Heer and D. Boyd. “Vizster: Visualizing online social networks”. In: *IEEE Symposium on Information Visualization, 2005. INFOVIS 2005.* IEEE. 2005, pp. 32–39.

169. J. Heer, N. Kong, and M. Agrawala. “Sizing the horizon: the effects of chart size and layering on the graphical perception of time series visualizations”. In: *Proceedings of the SIGCHI conference on human factors in computing systems*. 2009, pp. 1303–1312.

170. Hemma Ebner and Andrea Dillinger and Eva Mayr. *"Wer heilt hat recht": Ein Ausflug in die Salzburger Regionalmuseen auf den Spuren der Medizingeschichte*. URL: https://www.salzburgerregionalmuseen.at. Accessed: 2023-25-06.

171. D. Herman, M. Jahn, and M.-L. Ryan. *Routledge Encyclopedia of Narrative Theory*. Routledge, London, England, 2010. ISBN: 0415282594.

172. P. T. Hiller. “Visualizing the Intersection of the Personal and the Social Context–The Use of Multi-Layered Chronological Charts in Biographical Studies.” *Qualitative Report* 16:4, 2011, pp. 1018–1033.

173. Hische, Jessica and Maschmeyer, Russ. *Jess and Russ*. URL: http://jessandruss.us. Accessed: 2024-02-27.

174. T. R. Holtz Jr. *Dinosaurs: the most complete, up-to-date encyclopedia for dinosaur lovers of all ages*. Random House Books for Young Readers, 2007.

175. R. Hopfner. *Violinforensic*. http://www.violinforensic.com (Accessed 2019-06-24). 2018.

176. M. S. Horn, M. Tobiasz, and C. Shen. “Visualizing Biodiversity with Voronoi Treemaps”. In: *2009 Sixth International Symposium on Voronoi Diagrams*. 2009, pp. 265–270. DOI: 10.1109/ISVD.2009.22.

177. J. Hoskins. *Biographical objects: how things tell the stories of peoples' lives*. Routledge, 2013.

178. S. H. Hsu, J.-W. Chang, and C.-C. Lee. “Designing attractive gamification features for collaborative storytelling websites”. *Cyberpsychology, Behavior, and Social Networking* 16:6, 2013, pp. 428–435.

179. J. Hullman and N. Diakopoulos. “Visualization Rhetoric: Framing Effects in Narrative Visualization”. *IEEE Transactions on Visualization and Computer Graphics* 17:12, 2011, pp. 2231–2240. DOI: 10.1109/TVCG.2011.255.

180. J. Hullman, S. Drucker, N. Henry Riche, B. Lee, D. Fisher, and E. Adar. “A Deeper Understanding of Sequence in Narrative Visualization”. *IEEE Transactions on Visualization and Computer Graphics* 19:12, 2013, pp. 2406–2415. DOI: 10.1109/TVCG.2013.119.

181. Humanitarian Data Exchange. *The Humanitarian Data Exchange*. (Retrieved 2022-03-31). 2022.

182. Humap Limited. *Humap - The Interactive Map Platform*. URL: https://humap.me/. Accessed: 2023-25-06.

183. C. Humphries and A. C. Smith. “Talking objects: Towards a post-social research framework for exploring object narratives”. *Organization* 21:4, 2014, pp. 477–494.

184. D. H. Huson, D. C. Richter, C. Rausch, T. Dezulian, M. Franz, and R. Rupp. “Dendroscope: An interactive viewer for large phylogenetic trees”. *BMC bioinformatics* 8:1, 2007, pp. 1–6.

185. E. Hyvönen, P. Leskinen, M. Tamper, H. Rantala, E. Ikkala, J. Tuominen, and K. Keravuori. “BiographySampo–publishing and enriching biographies on the semantic web for digital humanities research”. In: *European Semantic Web Conference*. Springer. 2019, pp. 574–589.

186. Insider Science. *Map Shows How Humans Migrated Across The Globe*. URL: https://www.youtube.com/watch?v=CJdT6QcSbQ0. Accessed: 2023-25-06.

187. Institute of Information Science and Technologies "Alessandro Faedo" - ISTI. *story map building and visualising tool (smbvt) - building and visualising narratives in digital libraries*. URL: https://dlnarratives.eu/tool.html. Accessed: 2023-06-02.

188. InTaVia. *Smashing the Silos! The Future of Cultural Heritage Information and Visualization*. International Research Symposium, co-located with DH2023. https://intavia.eu/dh2023/. 2023.

189. International Council on Monuments and Sites. *Historic Gardens, The Florence Charter, Florence, Italy*. 1982.

190. J. J. Crump. *The Itinerary of King John the Rotuli Litterarum Patentium*. URL: https://neolography.com/timelines/JohnItinerary.html. Accessed: 2024-02-27.

191. I. P. Jääskeläinen, V. Klucharev, K. Panidi, and A. N. Shestakova. “Neural Processing of Narratives: From Individual Processing to Viral Propagation”. *Frontiers in Human Neuroscience* 14, 2020. ISSN: 1662-5161. DOI: 10.3389/fnhum.2020.00253.

192. F. Jahnel. *Die Gitarre und ihr Bau: Technologie von Gitarre, Laute, Mandoline, Sister, Tanbur und Saite*. 4. Aufl. Verl. Das Musikinstrument, Frankfurt a.M., 1981. ISBN: 3 920112 07 5.

193. S. Jänicke. “Timages: Enhancing time graphs with iconographic information”, 2018.

194. S. Jänicke. “Visual Exploration of the European Red List”. In: *Workshop on Visualisation in Environmental Sciences (EnvirVis)*. Ed. by R. Bujack, K. Feige, K. Rink, and D. Zeckzer. The Eurographics Association, 2019. ISBN: 978-3-03868-086-4. DOI: 10.2312/envirvis.20191103.

195. S. Jänicke, E. Beech, and M. Rivers. "Exploring the diversity and conservation status of tree species with TreeeX". *Environmental Earth Sciences* 78:21, 2019, pp. 1–10.

196. S. Jänicke, J. Blumenstein, M. Rücker, D. Zeckzer, and G. Scheuermann. "TagPies: Comparative Visualization of Textual Data." In: *Visigrapp (3: Ivapp)*. 2018, pp. 40–51.

197. S. Jänicke and J. Focht. "Untangling the Social Network of Musicians". In: *Book of Abstracts of DH2017*. Alliance of Digital Humanities Organizations. Montréal, Canada, 2017. URL: https://dh2017.adho.org/abstracts/002/002.pdf.

198. S. Jänicke, J. Focht, and G. Scheuermann. "Interactive Visual Profiling of Musicians". *IEEE Transactions on Visualization and Computer Graphics* 22:1, 2016, pp. 200–209. DOI: 10.1109/TVCG.2015.2467620.

199. S. Jänicke, J. Focht, and G. Scheuermann. "Interactive visual profiling of musicians". *IEEE transactions on visualization and computer graphics* 22:1, 2015, pp. 200–209.

200. S. Jänicke, G. Franzini, M. F. Cheema, and G. Scheuermann. "On Close and Distant Reading in Digital Humanities: A Survey and Future Challenges." In: *EuroVis (STARs)*. 2015, pp. 83–103.

201. S. Jänicke, G. Franzini, M. F. Cheema, and G. Scheuermann. "Visual text analysis in digital humanities". *Computer Graphics Forum* 36:6, 2017, pp. 226–250.

202. S. Jänicke, C. Heine, and G. Scheuermann. "Geotemco: Comparative visualization of geospatial-temporal data with clutter removal based on dynamic delaunay triangulations". In: *Computer Vision, Imaging and Computer Graphics. Theory and Application: 7th International Joint Conference, VISIGRAPP 2012, Rome, Italy, February 24-26, 2012, Revised Selected Papers*. Springer. 2013, pp. 160–175.

203. S. Jänicke, P. Kaur, P. Kuzmicki, and J. Schmidt. "Participatory Visualization Design as an Approach to Minimize the Gap between Research and Application." In: *VisGap@ Eurographics/EuroVis*. 2020, pp. 35–42.

204. S. Jänicke and G. Scheuermann. "Utilizing GeoTemCo for Visualizing Environmental Data". In: *Workshop on Visualisation in Environmental Sciences (EnvirVis)*. Ed. by O. Kolditz, K. Rink, and G. Scheuermann. The Eurographics Association, 2014. ISBN: 978-3-905674-66-8. DOI: 10.2312/envirvis.20141107.

205. J. Janicki, N. Narula, M. Ziegler, B. Guénard, and E. P. Economo. "Visualizing and interacting with large-volume biodiversity data using client–server web-mapping applications: The design and implementation of antmapsrg". *Ecological Informatics* 32, 2016, pp. 185–193.

206. W. Javed, B. McDonnel, and N. Elmqvist. "Graphical perception of multiple time series". *IEEE transactions on visualization and computer graphics* 16:6, 2010, pp. 927–934.

207. Jodi Cranston. *Mapping Paintings*. URL: https://www.mappingpaintings.org/maps. Accessed: 2024-02-27.

208. B. Jonson and B. Shneiderman. "Treemaps: a space-filling approach to the visualization of hierarchical information structure". In: *Proc. of th Second Internat. IEEE Visualization Conf.–1991*. 1991.

209. K. M. Jørgensen and P. Fatien. "Gaia storytelling: Management learning as terrestrial politics". *Organization*, 2024, p. 13505084231219771.

210. Josef Münzberger. *Dante's Inferno*. URL: `https://storymaps.arcgis.com/stories/ad2a09720b75435b922396307e2d6004`. Accessed: 2023-25-06.

211. M. Joubert, L. Davis, and J. Metcalfe. *Storytelling: The Soul of Science Communication*. 2019.

212. Y. E. Kalay, T. Kvan, and J. Affleck. *New Heritage: New Media and Cultural Heritage*. Routledge, 2007.

213. P. Kampstra et al. "Beanplot: A boxplot alternative for visual comparison of distributions", 2008.

214. D. Kang, T. Ho, N. Marquardt, B. Mutlu, and A. Bianchi. "ToonNote: Improving Communication in Computational Notebooks Using Interactive Data Comics". In: *CHI '21: CHI Conference on Human Factors in Computing Systems, Virtual Event / Yokohama, Japan, May 8-13, 2021*. Ed. by Y. Kitamura, A. Quigley, K. Isbister, T. Igarashi, P. Bjørn, and S. M. Drucker. ACM, 2021, 727:1–727:14. DOI: `10.1145/3411764.3445434`. URL: `https://doi.org/10.1145/3411764.3445434`.

215. F. Kaplan and I. Di Lenardo. "The advent of the 4D mirror world". *Urban Planning* 5:ARTICLE, 2020, p. 307.

216. H. Karner. *Die Wiener Hofburg 1521–1705. Baugeschichte, Funktion und Etablierung als Kaiserresidenz*. Verlag der ÖAW, 2014.

217. R. Khulusi, J. Kusnick, C. Meinecke, C. Gillmann, J. Focht, and S. Jänicke. "A Survey on Visualizations for Musical Data". *Computer Graphics Forum*, 2020. ISSN: 1467-8659. DOI: `10.1111/cgf.13905`.

218. R. Khulusi. "Visuelle Analyse von Chronologien aus den Karrieren von Zupfinstrumenten, ihrer Spieler und Hersteller". *Phoibos-Zeitschrift für Zupfmusik* 19, 2021, pp. 51–60.

219. R. Khulusi, S. Billib, and S. Jänicke. "Exploring Life in Concentration Camps through a Visual Analysis of Prisonersrsquo; Diaries". *Information* 13:2, 2022. ISSN: 2078-2489. DOI: `10.3390/info13020054`. URL: `https://www.mdpi.com/2078-2489/13/2/54`.

220. R. Khulusi, J. Kusnick, J. Focht, and S. Jänicke. "An interactive chart of biography". In: *2019 IEEE Pacific Visualization Symposium (PacificVis)*. IEEE. 2019, pp. 257–266.

221. R. Khulusi, J. Kusnick, J. Focht, and S. Jänicke. "MusiXplora: Visual analysis of a musicological encyclopedia". English. In: *Proceedings of the 15th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications*. Ed. by A. Kerren, C. Hurter, and J. Braz. Vol. 3. IVAPP. 15th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications, VISIGRAPP 2020 ; Conference date: 27-02-2020 Through 29-02-2020. SCITEPRESS Digital Library, 2020, pp. 76–87. DOI: `10.5220/0008977100760087`.

222. R. Khulusi, J. Kusnick, J. Focht, and S. Jänicke. "musiXplora: Visual Analysis of a Musicological Encyclopedia." In: *VISIGRAPP (3: IVAPP)*. 2020, pp. 76–87.

223. R. Khulusi, J. Kusnick, J. Focht, and S. Jänicke. "musiXplora: Visual Analysis of Musicological Data". In: *Proceedings of the 11th International Conference on Information Visualization Theory and Applications (IVAPP)*. 2020.

224. R. Khulusi, J. Kusnick, C. Meinecke, C. Gillmann, J. Focht, and S. Jänicke. "A survey on visualizations for musical data". In: *Computer Graphics Forum*. Vol. 39. 6. Wiley Online Library. 2020, pp. 82–110.

225. G. Kim, J. Kim, J. Son, and H.-S. Lim. "KOCHET: a Korean Cultural Heritage corpus for Entity-related Tasks". In: *Proceedings of the 29th International Conference on Computational Linguistics*. 2022, pp. 3496–3505.

226. N. W. Kim, B. Bach, H. Im, S. Schriber, M. Gross, and H. Pfister. "Visualizing Nonlinear Narratives with Story Curves". *IEEE Transactions on Visualization and Computer Graphics* 24:1, 2018, pp. 595–604. DOI: 10.1109/TVCG.2017.2744118.

227. N. W. Kim, N. Henry Riche, B. Bach, G. A. Xu, M. Brehmer, K. Hinckley, M. Pahud, H. Xia, M. McGuffin, and H. Pfister. "DataToon: Drawing Dynamic Network Comics With Pen + Touch Interaction". In: *CHI 2019*. Association for Computing Machinery. 2019, pp. 1–12. URL: https://www.microsoft.com/en-us/research/publication/datatoon-drawing-dynamic-network-comics-with-pen-touch-interaction/.

228. N. W. Kim, N. H. Riche, B. Bach, G. Xu, M. Brehmer, K. Hinckley, M. Pahud, H. Xia, M. McGuffin, and H. Pfister. *DataToon - A flexible data comic storyboarding tool that blends analysis and presentation with pen and touch interactions*. URL: https://datatoon.github.io/. Accessed: 2022-10-07.

229. S. Kirsch. "Computed Tomography as a Tool for Archiving Ethnomusicological Objects". In: *Computational Phonogram Archiving*. Ed. by R. Bader. Springer International Publishing, Cham, 2019, pp. 305–319. ISBN: 978-3-030-02695-0. DOI: 10.1007/978-3-030-02695-0_14. URL: https://doi.org/10.1007/978-3-030-02695-0_14.

230. L. F. Klein. "The image of absence: archival silence, data visualization, and James Hemings". *American Literature* 85:4, 2013, pp. 661–688.

231. Klein, Matthew C. *How Americans Die*. URL: https://www.bloomberg.com/graphics/dataview/how-americans-die/. Accessed: 2024-02-27.

232. T. Kluyver, B. Ragan-Kelley, F. Pérez, B. E. Granger, M. Bussonnier, J. Frederic, K. Kelley, J. B. Hamrick, J. Grout, S. Corlay, P. Ivanov, D. Avila, S. Abdalla, C. Willing, and J. D. Team. "Jupyter Notebooks - a publishing format for reproducible computational workflows". In: *International Conference on Electronic Publishing*. 2016.

233. Knight Lab. *Arya's Jouney*. URL: https://storymap.knightlab.com/examples/aryas-journey//. Accessed: 2023-08-17.

234. Knight Lab. *StoryLine - Tell the story behind the numbers*. URL: https://storyline.knightlab.com/. Accessed: 2023-06-02.

235. Knight Lab. *StoryMap - Maps that tell stories*. URL: https://storymap.knightlab.com. Accessed: 2021-09-04.

236. Knight Lab. *Timeline - Easy-to-make, beautiful timelines*. URL: https://timeline.knightlab.com. Accessed: 2021-09-04.

237. Knight Lab. *Whitney Houston*. URL: https://timeline.knightlab.com/examples/houston/index.html. Accessed: 2021-09-04.

238. S. G. Kobourov. "Spring embedders and force directed graph drawing algorithms". *arXiv preprint arXiv:1201.3011*, 2012.

239. A. Kölble. "The Brazilian Pantanal as an Ecomusicosystem". *Journal of Cultural Management and Cultural Policy / Zeitschrift für Kulturmanagement und Kulturpolitik* 2, 2023. ISSN: 2701-8466.

240. M. Koolen, J. Kamps, and V. de Keijzer. "Information retrieval in cultural heritage". *Interdisciplinary Science Reviews* 34:2-3, 2009, pp. 268–284.

241. I. Kopytoff. "The cultural biography of things: commoditization as process". *The social life of things: Commodities in cultural perspective* 68, 1986, pp. 70–73.

242. R. Kosara. "An Argument Structure for Data Stories". In: *Proceedings of the Eurographics/IEEE VGTC Conference on Visualization: Short Papers*. EuroVis '17. Eurographics Association, Barcelona, Spain, 2017, pp. 31–35. DOI: 10.2312/eurovisshort.20171129.

243. R. Kosara. *Story: A Definition*. URL: https://eagereyes.org/blog/2014/story-a-definition. Accessed: 2022-07-04. 2014.

244. S. Krähenmann. "Animals as Specially Protected Objects". In: pp. 92–108.

245. M. Krstajic, E. Bertini, and D. Keim. "Cloudlines: Compact display of event episodes in multiple time-series". *IEEE transactions on visualization and computer graphics* 17:12, 2011, pp. 2432–2439.

246. R. Kurdiovsky, G. Buchinger, R. Holzschuh-Hofer, M. Jeitler, H. Karner, A. Mader-Kratky, and W. Telesko. "Legitimacy through History and Architecture. The Vienna Hofburg as Dynastic Hub and Seat of Government between Tradition and Innovation". *The Court Historian* 20(2), 2015, pp. 109–136.

247. J. Kusnick, S. Jaenicke, C. Doppler, K. Seirafi, J. Liem, F. Windhager, and E. Mayr. *Report on Narrative Visualization Techniques for OPDB Data*. Technical report. InTaVia project, 2021. URL: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5e47d9524&appId=PPGMS.

248. J. Kusnick. *Design und Implementierung einer Anwendung zur interaktiven Visualisierung von CT-Daten im Museumsumfeld*. Master's Thesis, 2018.

249. J. Kusnick. "Design und Implementierung einer Anwendung zur interaktiven Visualisierung von CT-Daten im Museumsumfeld". MA thesis. Leipzig University, Leipzig, Germany, 2018.

250. J. Kusnick, J. Focht, and S. Jänicke. "Visualizing the Aura of Musical Instruments". In: *Proceedings of 2nd EADH conference 'Interdisciplinary Perspectives on Data', 2021, Krasnoyarsk, Russia*. 2021.

251. J. Kusnick, S. Jänicke, C. Doppler, K. Seirafi, J. Liem, F. Windhager, and E. Mayr. *Report on Narrative Visualization Techniques for OPDB Data*. URL: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5e47d9524&appId=PPGMS. Deliverable within the H2020 project InTaVia. 2021.

252. J. Kusnick, R. Khulusi, J. Focht, and S. Jänicke. "A Timeline Metaphor for Analyzing the Relationships between Musical Instruments and Musical Pieces." In: *VISIGRAPP (3: IVAPP)*. 2020, pp. 240–251.

253. J. Kusnick, S. Lichtenberg, and S. Jänicke. "Visualization-based Scrollytelling of Coupled Threats for Biodiversity, Species and Music Cultures". In: *Workshop on Visualisation in Environmental Sciences (EnvirVis)*. Ed. by S. Dutta, K. Feige, K. Rink, and D. Zeckzer. The Eurographics Association, 2023. ISBN: 978-3-03868-223-3. DOI: 10.2312/envirvis.20231112.

254. J. Kusnick, S. Lichtenberg, D. Wiegreffe, E. Huber-Sannwald, U. Nehren, and S. Jänicke. "Visual Analysis of Diversity and Threat Status of Natural Materials for Musical Instruments". Submitted to the journal Frontiers in Environmental Science. 2024.

255. J. Kusnick, E. Mayr, K. Seirafi, S. Beck, J. Liem, and F. Windhager. "Every Thing Can Be a Hero! Narrative Visualization of Person, Object, and Other Biographies". Submitted to the journal informatics. 2024.

256. J. Kusnick, N. Sindlev Andersen, J. Liem, E. Mayr, S. Beck, S. Koch, C. Doppler, K. Seirafi, S. Jänicke, and F. Windhager. "A Survey on Visualization-based Storytelling in Digital Humanities and Cultural Heritage". Submitted to the journal Visual Informatics. 2024.

257. S. L'Yi, J. Jo, and J. Seo. "Comparative Layouts Revisited: Design Space, Guidelines, and Future Directions". *IEEE Transactions on Visualization & Computer Graphics* 27:02, 2021. Place: Los Alamitos, CA, USA Publisher: IEEE Computer Society, pp. 1525–1535. ISSN: 1941-0506. DOI: 10.1109/TVCG.2020.3030419.

258. J. Lankow, J. Ritchie, and R. Crooks. *Infographics: The power of visual storytelling*. John Wiley & Sons, 2012.

259. S. Latif, S. Chen, and F. Beck. "A Deeper Understanding of Visualization-Text Interplay in Geographic Data-driven Stories". *Computer Graphics Forum* 40:3, 2021, pp. 311–322. DOI: 10.1111/cgf.14309.

260. S. Latif, S. Chen, and F. Beck. "A Deeper Understanding of Visualization-Text Interplay in Geographic Data-driven Stories". *Computer Graphics Forum* 40, 2021, pp. 311–322.

261. Leaflet.markercluster — Marker Clustering plugin for Leaflet. *Leaflet.markercluster*. (Retrieved 2022-03-31). 2022.

262. 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* 35:5, 2015, pp. 84–90.

263. J. K. Lee. "Digital history in the history/social studies classroom". *The history teacher* 35:4, 2002, pp. 503–517. DOI: 10.2307/1512472.

264. E. Legg and P. Sullivan. "Storytelling as a balancing practice in the study of posthuman praxis". *Posthuman praxis in technical communication*, 2018, pp. 23–45.

265. P. Lehohla. *OPINION: Digital colonialism on the African continent*. URL: https://www.iol.co.za/business-report/opinion/opinion-digital-colonialism-on-the-african-continent-17493010. Accessed: 2024-03-30.

266. G. M. Leon, M. Lischka, and A. Breiter. "Mapping the Global South: Equal-Area Projections for Choropleth Maps". *Cartographic Perspectives* 59, 2008, pp. 91–95. ISSN: 1048-9053. DOI: 10.1109/VIS47514.2020.00025.

267. P. Leskinen, E. Hyvönen, and J. Tuominen. "Analyzing and Visualizing Prosopographical Linked Data Based on Biographies". In: *Proceedings of the Second Conference on Biographical Data in a Digital World 2017 (BD2017)*. CEUR Workshop Proceedings. 2017.

268. I. Letunic and P. Bork. "Interactive Tree Of Life (iTOL) v5: an online tool for phylogenetic tree display and annotation". *Nucleic Acids Research* 49:W1, 2021, W293–W296. ISSN: 0305-1048. DOI: 10.1093/nar/gkab301. URL: https://doi.org/10.1093/nar/gkab301 (visited on 03/24/2022).

269. S. Lichtenberg, E. Huber-Sannwald, J. A. Reyes-Agüero, D. Anhuf, and U. Nehren. "Pau-brasil and string instrument bows telecouple nature, art, and heritage". *Ecology and Society* 27:1, 2022, pp. 1–21. ISSN: 1708-3087. DOI: 10.5751/ES-13047-270132.

270. J. Liem, J. Kusnick, S. Beck, F. Windhager, and E. Mayr. "A Workflow Approach to Visualization-Based Storytelling with Cultural Heritage Data". In: *2023 IEEE 8th Workshop on Visualization for the Digital Humanities (VIS4DH)*. 2023, pp. 13–17. DOI: 10.1109/VIS4DH60378.2023.00008.

271. J. Liem, J. Kusnick, S. Beck, F. Windhager, and E. Mayr. "A Workflow Approach to Visualization-Based Storytelling with Cultural Heritage Data". In: *2023 IEEE 7th Workshop on Visualization for the Digital Humanities (VIS4DH)*. 2023 (in publication).

272. A. Liu. *Where is cultural criticism in the digital humanities?* eScholarship, University of California, 2012.

273. W. S. Logan. "Closing Pandora's Box: Human Rights Conundrums in Cultural Heritage Protection". In: *Cultural Heritage and Human Rights*. Ed. by H. Silverman and D. F. Ruggles. Springer New York, New York, NY, 2007, pp. 33–52. ISBN: 978-0-387-71313-7. DOI: 10.1007/978-0-387-71313-7_2. URL: https://doi.org/10.1007/978-0-387-71313-7_2.

274. London Symphony Orchestra. *LSO Play: Stravinsky's The Rite of Spring, Instruments View*. https://play.lso.co.uk/performances/Stravinskys-The-Rite-of-Spring/explore/instruments. (Retrieved 2022-03-31). 2022.

275. H. W. Longfellow. *Outre-mer: A pilgrammage beyond the sea*. G. Routledge & Company, 1857.

276. D. Longo, A. Boeri, B. Turillazzi, and S. Orlandi. "Cultural heritage and interoperable open platforms: strategies for knowledge, accessibility, enhancement and networking". *WIT Transactions on Ecology and the Environment* 241, 2020, pp. 371–382.

277. H. Lorenz and A. Mader-Kratky. *Die Wiener Hofburg 1705–1835. Die kaiserliche Residenz vom Barock bis zum Klassizismus*. Verlag der ÖAW, 2016.

278. S. Loriga. "The plurality of the past: Historical time and the rediscovery of biography". In: *The Biographical Turn*. Routledge, 2016, pp. 47–57.

279. J. Lu, W. Chen, H. Ye, J. Wang, H. Mei, Y. Gu, Y. Wu, X. L. Zhang, and K.-L. Ma. "Automatic Generation of Unit Visualization-based Scrollytelling for Impromptu Data Facts Delivery". In: *2021 IEEE 14th Pacific Visualization Symposium (PacificVis)*. 2021, pp. 21–30. DOI: 10.1109/PacificVis52677.2021.00011.

280. Lu, Susie and Akred, John. *The History of Rock in 100 Sings*. URL: https://svds.com/rockandroll. Accessed: 2024-02-27.

281. K.-L. Ma, I. Liao, J. Frazier, H. Hauser, and H.-N. Kostis. "Scientific Storytelling Using Visualization". *IEEE Computer Graphics and Applications* 32:1, 2012, pp. 12–19. DOI: 10.1109/MCG.2012.24.

282. E. Mäkelä, E. Hyvönen, and T. Ruotsalo. "How to deal with massively heterogeneous cultural heritage data–lessons learned in CultureSampo". *Semantic Web* 3:1, 2012, pp. 85–109.

283. MapLibre. *Open-source mapping libraries for web and mobile app developers*. https://maplibre.org/. [accessed 10-July-2023].

284. B. Marr. *Using VR To Step Inside Your Data: VR Or AR-Enabled Analytics*. URL: https://www.forbes.com/sites/bernardmarr/2021/02/12/using-vr-to-step-inside-your-data-vr-or-ar-enabled-analytics. Accessed: 2022-07-04. 2021.

285. Mary Kearn. *The Life of Mary Kearn*. URL: https://www.tiki-toki.com/timeline/entry/67/The-Life-of-Mary-Kearns/. Accessed: 2023-25-06.

286. Matt Daniels. *Are men singing higher in pop songs today?* URL: https://pudding.cool/2019/08/register/. Accessed: 2023-25-06.

287. E. Mayr, G. Pobežin, M. Schlögl, J. Liem, and F. Windhager. *Linking and visualizing cultural heritage data for humanities research*. Version 1. Poster presented at the DARIAH annual event. 2023. DOI: 10.5281/zenodo.8004479. URL: https://doi.org/10.5281/zenodo.8004479.

288. E. Mayr, S. Salisu, V. A. Filipov, G. Schreder, R. A. Leite, S. Miksch, and F. Windhager. "Visualizing biographical trajectories by historical artifacts: a case study based on the photography collection of Charles W. Cushman". In: *Proceedings of BD 2019*. 2022.

289. E. Mayr and F. Windhager. "Once upon a spacetime: Visual storytelling in cognitive and geotemporal information spaces". *ISPRS International Journal of Geo-Information* 7:3, 2018, p. 96.

290. E. Mayr, F. Windhager, J. Liem, S. Beck, S. Koch, J. Kusnick, and S. Jänicke. "The Multiple Faces of Cultural Heritage: Towards an Integrated Visualization Platform for Tangible and Intangible Cultural Assets". In: *2022 IEEE 7th Workshop on Visualization for the Digital Humanities (VIS4DH)*. 2022, pp. 13–18. DOI: 10.1109/VIS4DH57440.2022.00008.

291. E. Mayr, F. Windhager, J. Liem, S. Beck, S. Koch, J. Kusnick, and S. Jänicke. “The multiple faces of cultural heritage: Towards an integrated visualization platform for tangible and intangible cultural assets”. In: *2022 IEEE 7th Workshop on Visualization for the Digital Humanities (VIS4DH)*. IEEE. 2022, pp. 13–18.

292. Mayr, Eva and Kusnick, Jakob and Liem, Johannes and Passecker, Markus and Kaiser, Maximilian. *Report on Usability of Narrative Visualizations*. Technical report. H2020 project InTaVia, 2023.

293. S. McCloud. *Understanding Comics*. Kitchen Sink Press, 1993.

294. T. e. a. Mchedlidze. “Network Visualization Challenges and Opportunities in Digital Humanities”. *Journal of Historical Network Research (to be published)*, 2019.

295. G. Mckee. “The Map as a Search Box: Using Linked Data to Create a Geographic Discovery System”. *Information Technology and Libraries* 38:1, 2019, pp. 40–52. DOI: 10.6017/ital.v38i1.10592. URL: https://ital.corejournals.org/index.php/ital/article/view/10592.

296. S. McKenna, N. Henry Riche, B. Lee, J. Boy, and M. Meyer. “Visual Narrative Flow: Exploring Factors Shaping Data Visualization Story Reading Experiences”. *Comput. Graph. Forum* 36:3, 2017, pp. 377–387. ISSN: 0167-7055. DOI: 10.1111/cgf.13195.

297. L. McNabb and R. S. Laramee. “How to Write a Visualization Survey Paper: A Starting Point”. In: *Eurographics (Education Papers)*. 2019, pp. 29–39.

298. G. McNeill and S. A. Hale. “Generating tile maps”. In: *Computer Graphics Forum*. Vol. 36. 3. Wiley Online Library. 2017, pp. 435–445.

299. C. Meinecke. “Labeling of cultural heritage collections on the intersection of visual analytics and digital humanities”. In: *2022 IEEE 7th Workshop on Visualization for the Digital Humanities (VIS4DH)*. IEEE. 2022, pp. 19–24.

300. C. Meinecke, C. Hall, and S. Jänicke. “Towards Enhancing Virtual Museums by Contextualizing Art through Interactive Visualizations”. *J. Comput. Cult. Herit.* 15:4, 2022. ISSN: 1556-4673. DOI: 10.1145/3527619. URL: https://doi.org/10.1145/3527619.

301. C. Meinecke and S. Jänicke. “Visual Analysis of Engineers’ Biographies and Engineering Branches”. In: *LEVIA18: Leipzig Symposium on Visualization in Applications*. 2018.

302. D. R. Meister. “The biographical turn and the case for historical biography”. *History Compass* 16:1, 2018, e12436.

303. M. Meuschke, L. A. Garrison, N. N. Smit, B. Bach, S. Mittenentzwei, V. Weiß, S. Bruckner, K. Lawonn, and B. Preim. “Narrative medical visualization to communicate disease data”. *Computers & Graphics* 107, 2022, pp. 144–157.

304. Michelle McGhee. *Wonky*. URL: https://pudding.cool/2023/06/groove/. Accessed: 2023-25-06.

305. Microsoft Power BI. *Power BI - Turn your data into immediate impact*. URL: https://powerbi.microsoft.com/. Accessed: 2023-06-02.

306. M. Miller, J. Walloch, and M. C. Pattuelli. "Visualizing linked Jazz: A web-based tool for social network analysis and exploration". *Proceedings of the American Society for Information Science and Technology* 49:1, 2012, pp. 1–3.

307. O. Möckel. *Die Kunst des Geigenbaues: Mit 53 Tafeln; vocabulary of violin terms in German, English, French and Italian on page 372*. 8. Voigt, Hamburg, 1997. ISBN: 9783582001009.

308. H. Möller, J. Pätynen, S. Tervo, and T. Lokki. "Practical application and analysis of full orchestra spatial impulse responses in an opera house". *Proceedings of IOA Auditorium Acoustics, Paris, France*, 2015.

309. P. Morgades, A. Slingsby, and J. Moat. "Assessing the Geographical Structure of Species Richness Data with Interactive Graphics". In: *Workshop on Visualisation in Environmental Sciences (EnvirVis)*. The Eurographics Association. 2021.

310. P. A. Moro. *Violins: Local meanings, globalized sounds*. Routledge, New York NY, 2019.

311. E. Mörth, S. Bruckner, and N. N. Smit. "ScrollyVis: Interactive visual authoring of guided dynamic narratives for scientific scrollytelling". *IEEE Transactions on Visualization and Computer Graphics*, 2022.

312. S. Münster, F. Apollonio, P. Bell, P. Kuroczynski, I. Di Lenardo, F. Rinaudo, and R. Tamborrino. "Digital cultural heritage meets digital humanities". In: *27Th Cipa International Symposium: Documenting The Past For A Better Future*. CONF. INTL SOC PHOTOGRAMMETRY & REMOTE SENSING-ISPRS. 2019, pp. 812–820.

313. T. Munzner. "A nested model for visualization design and validation". *IEEE transactions on visualization and computer graphics* 15:6, 2009, pp. 921–928. DOI: 10.1109/TVCG.2009.111.

314. T. Munzner. *Visualization analysis and design*. CRC press, 2014.

315. J. M. Musacchio. *Mapping the "White, Marmorean Flock": Anne Whitney Abroad, 1867–1868*. URL: http://www.19thc-artworldwide.org/index.php/autumn14/musacchio-mapping-a-member-of-the-white-marmorean-flock#. Accessed: 2021-09-04.

316. Mused, Inc. *Mused*. URL: http://mused.org. Accessed: 2024-02-27.

317. *Musical Instrument Museums Online*. 2011. URL: https://mimo-international.com/MIMO.

318. R. Nararatwong, N. Kertkeidkachorn, and R. Ichise. "Knowledge graph visualization: challenges, framework, and implementation". In: *2020 IEEE Third International Conference on Artificial Intelligence and Knowledge Engineering (AIKE)*. IEEE. 2020, pp. 174–178.

319. Narralive. *Story Maker - Narralive*. URL: https://www.narralive.org/story-maker/. Accessed: 2023-06-02.

320. D. Nasaw. *Historians and Biography Introduction*. 2009.

321. Nedkova, Kristina and Vakhitova, Sabina and Mizinov, Leonid and Zotova, Anastasiya and Trzhemetsky, Gleb and Mizinov, Anton and Novichkov, Alexey (TASS). *When Napoleon Ventured East*. URL: https://1812.tass.ru/en. Accessed: 2023-25-06.

322. New York Times. *Notre-Dame came far closer to collapsing than people knew. This is how it was saved.* URL: https://www.nytimes.com/interactive/2019/07/16/world/europe/notre-dame.html. Accessed: 2023-01-27.

323. F. Niccolucci, A. Felicetti, and S. Hermon. "Populating the Data Space for Cultural Heritage with Heritage Digital Twins". *Data* 7:8, 2022. ISSN: 2306-5729. DOI: 10.3390/data7080105. URL: https://www.mdpi.com/2306-5729/7/8/105.

324. M. C. Nisbet. *The Ethics of Framing Science*. Routledge, 2012, pp. 51–74.

325. Northwestern University Knight Lab. *US Westward Expansion*. URL: https://storymap.knightlab.com/. Accessed: 2023-25-06.

326. 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: *2014 18th International Conference on Information Visualisation*. IEEE. 2014, pp. 241–250.

327. S. Nowak, L. Bartram, and T. Schiphorst. "A Micro-Phenomenological Lens for Evaluating Narrative Visualization". In: *2018 IEEE Evaluation and Beyond - Methodological Approaches for Visualization (BELIV)*. 2018, pp. 11–18. DOI: 10.1109/BELIV.2018.8634072.

328. NSS EPALE Nederland. *GreenerAge – promoting climate change literacy and promoting sustainable behaviours through gamification for citizens 55+.* URL: https://epale.ec.europa.eu/en/blog/greenerage-promoting-climate-change-literacy-and-promoting-sustainable-behaviours-through. Accessed: 2023-03-09.

329. J. Nyhan, M. Terras, and E. Vanhoutte. *Defining Digital Humanities*. Burlington, VT: Ashgate, 2013.

330. J. O'Sullivan. *The Bloomsbury Handbook to the Digital Humanities*. Bloomsbury Publishing, 2022.

331. A. Oakley. "The social science of biographical life-writing: some methodological and ethical issues". *International Journal of Social Research Methodology* 13:5, 2010, pp. 425–439.

332. V. Okanovic, I. Ivkovic-Kihic, D. Boskovic, B. Mijatovic, I. Prazina, E. Skaljo, and S. Rizvic. "Interaction in extended reality applications for cultural heritage". *Applied Sciences* 12:3, 2022, p. 1241.

333. D. M. Olson et al. "Terrestrial Ecoregions of the World: A New Map of Life on Earth". *BioScience* 51:11, 2001, p. 933. ISSN: 0036-8075. DOI: 10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2.

334. J. Ossmann, K. Seirafi, and C. Doppler. "Four Ways to Experience Augmented Reality at Museums." *Methis* 22, 2021.

335. T. Padilla. "On a collections as data imperative", 2017.

336. *Palladio. Visualize complex historical data with ease.* URL: http://hdlab.stanford.edu/palladio/. Accessed: 2021-09-04.

337. G. Palma, M. Baldassarri, M. C. Favilla, and R. Scopigno. "Storytelling of a Coin Collection by Means of RTI Images: the Case of the Simoneschi Collection in Palazzo Blu". In: *Museums and the Web 2014*. Ed. by N. P. bibinitperiod R. Cherry. Silver Spring, 2014. URL: http://vcg.isti.cnr.it/Publications/2014/PBFS14.

338. D. Park, M. Suhail, M. Zheng, C. Dunne, E. Ragan, and N. Elmqvist. "StoryFacets: A design study on storytelling with visualizations for collaborative data analysis". *Information Visualization* 21:1, 2022, pp. 3–16. DOI: 10.1177/14738716211032653.

339. Paulus Bowparts. *Paulus Bowparts*. (Retrieved 2022-03-25). 2022.

340. M. A. Pérez and E. Marconi, eds. *Wooden musical instruments different forms of knowledge: Book of end of WoodMusICK COST Action FP1302*. Cité de la Musique and Présence Graphique, Paris and Monts, 2018. ISBN: 979-10-94642-35-1.

341. I. Perez-Messina, C. Gutierrez, and E. Graells-Garrido. "Organic Visualization of Document Evolution". In: *23rd International Conference on Intelligent User Interfaces*. IUI '18. Association for Computing Machinery, Tokyo, Japan, 2018, pp. 497–501. ISBN: 9781450349451. DOI: 10.1145/3172944.3173004. URL: https://doi.org/10.1145/3172944.3173004.

342. L. Peura. *Case Lake Tuusula – a Prosopographical Demo Using the Storytelling Suite*. Ljubljana, 2023. URL: https://youtu.be/l-S7t1tlIQ0?si=-wWYjxHiuth802AO.

343. Philharmonie de Paris. *Acquisitions 2016 du Musée de la musique*. URL: https://artsandculture.google.com/story/swWhCVRai9hsJA. Accessed: 2023-03-09.

344. D. Pilgrim. *Watermelons, Nooses, and Straight Razors: Stories from the Jim Crow Museum*. Pm Press, 2017.

345. T. d. O. Pinto. "Musik, implizites Wissen und immaterielles Kulturerbe". *Paragrana* 23:2, 2014. ISSN: 0938-0116. DOI: 10.1515/para-2014-0220.

346. A. Piper. "There Will be Numbers". *Journal of Cultural Analytics* 1:1, 2016.

347. R. de Prisco, N. Lettieri, D. Malandrino, D. Pirozzi, G. Zaccagnino, and R. Zaccagnino. "Visualization of Music Plagiarism: Analysis and Evaluation". In: *2016 20th International Conference Information Visualisation (IV)*. 2016, pp. 177–182. DOI: 10.1109/IV.2016.56.

348. QlikTech International AB. *Qlik Sense - Go from passive to active analytics*. URL: https://www.qlik.com/us/products/qlik-sense. Accessed: 2023-06-02.

349. Rabinowitz, Adam. *Archaeology of Wine*. URL: https://timemapper.okfnlabs.org/adamrabinowitz/archaeowinetimeliner. Accessed: 2023-25-06.

350. C. Raffensperger. "Visualizing Prosopography through Digital Humanities". *Medieval Prosopography* 34, 2019, pp. 207–220.

351. M. Ragnedda and G. W. Muschert. *The digital divide*. Routledge Florence, KY, 2013.

352. M. Ravankhah, R. de Wit, M. Revez, A. Chliaoutakis, A. Argyriou, I. V. Pinto, P. Brum, M. Žuvela-Aloise, et al. "Risk assessment and risk management for the protection of cultural heritage". *Cultural heritage resilience against climate change and natural hazards: Methodologies, procedures, technologies and policy improvements achieved by Horizon 2020–700191 STORM project*, 2019, pp. 55–88.

353. React. *The library for web and native user interfaces*. https://react.dev/. [accessed 10-July-2023].

354. React.js. *React - A JavaScript library for building user interfaces*. (Retrieved 2022-03-31). 2022.

355. M. Reckziegel, M. Cheema, G. Scheuermann, and S. Janicke. "Predominance Tag Maps". *IEEE Transactions on Visualization & Computer Graphics* 24:06, 2018, pp. 1893–1904. ISSN: 1941-0506. DOI: 10.1109/TVCG.2018.2816208.

356. M. Reinert, M. Schrott, B. Ebneth, and M. Rehbein. "From Biographies to Data Curation-The Making of www. deutsche-biographie. de." In: *BD*. 2015, pp. 13–19.

357. D. Ren, M. Brehmer, B. Lee, T. Höllerer, and E. K. Choe. "ChartAccent: Annotation for data-driven storytelling". In: *2017 IEEE Pacific Visualization Symposium (PacificVis)*. 2017, pp. 230–239. DOI: 10.1109/PACIFICVIS.2017.8031599.

358. H. Renders. "Biography as a Correction to History". *Les Grandes Figures historiques dans les lettres et les arts* 2017:2, 2017, pp. 31–37.

359. H. Renders, B. De Haan, and J. Harmsma. *The biographical turn: Lives in history*. Taylor & Francis, 2016.

360. *Répertoire International des Sources Musicales*. 1952. URL: https://rism.info.

361. T.-M. Rhyne, M. Tory, T. Munzner, M. O. Ward, C. R. Johnson, and D. H. Laidlaw. "Information and Scientific Visualization: Separate but Equal or Happy Together at Last." In: *IEEE Visualization*. Vol. 3. Seattle. 2003, pp. 611–614.

362. Richard Spencer. *Fleeing Syria for Europe: Safaa's fatal journey*. URL: https://s.telegraph.co.uk/graphics/projects/safaas-journey/index.html. Accessed: 2024-02-27.

363. N. H. Riche, C. Hurter, N. Diakopoulos, and S. Carpendale. *Data-driven storytelling*. CRC Press, 2018.

364. H. G. Richter. *Holz als Rohstoff für den Musikinstrumentenbau*. Vol. 4043. Edition Moeck. Moeck, Celle, 1988. ISBN: 3875490355.

365. S. Rizvic, D. Boskovic, V. Okanovic, S. Sljivo, and M. Zukic. "Interactive digital storytelling: bringing cultural heritage in a classroom". *Journal of Computers in Education* 6, 2019, pp. 143–166.

366. S. Rizvic, N. Djapo, F. Alispahic, B. Hadzihalilovic, F. F. Cengic, A. Imamovic, V. Okanovic, and D. Boskovic. "Guidelines for interactive digital storytelling presentations of cultural heritage". In: *2017 9th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games)*. IEEE. 2017, pp. 253–259.

367. 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. (Visited on 09/08/2016).

368. N. Rokotyan, O. Stukova, K. D., and D. Ovsyannikov. *Cosmograph: GPU-accelerated Force Graph Layout and Rendering*. URL: https://cosmograph.app/. 2022.

369. M. Rontani. *Patrimonito: a visual storytelling of World Heritage from and for children*.

370. R. E. Roth. "Cartographic Design as Visual Storytelling: Synthesis and Review of Map-Based Narratives, Genres, and Tropes". *The Cartographic Journal* 58:1, 2021, pp. 83–114. DOI: 10.1080/00087041.2019.1633103.

371. S. Ruecker, M. Radzikowska, and S. Sinclair. *Visual interface design for digital cultural heritage: A guide to rich-prospect browsing*. Routledge, 2016.

372. B. Ruefenacht, M. Finco, M. Nelson, R. Czaplewski, E. Helmer, J. Blackard, G. Holden, A. Lister, D. Salajanu, D. Weyermann, et al. "Conterminous US and Alaska forest type mapping using forest inventory and analysis data". *Photogrammetric Engineering & Remote Sensing* 74:11, 2008, pp. 1379–1388.

373. I. Russo, T. Caselli, and M. Monachini. "Extracting and Visualising Biographical Events from Wikipedia." In: *BD*. 2015, pp. 111–115.

374. M.-L. Ryan. *Narrative across Media: The Languages of Storytelling (Frontiers of Narrative)*. University of Nebraska Press, Lincoln, NE, USA, 2004.

375. A. Satyanarayan and J. Heer. "Authoring Narrative Visualizations with Ellipsis". In: *Proceedings of the 16th Eurographics Conference on Visualization*. EuroVis '14. Eurographics Association, Swansea, Wales, United Kingdom, 2014, pp. 361–370.

376. A. Scharl, A. Hubmann-Haidvogel, M. Göbel, T. Schäfer, D. Fischl, and L. Nixon. "Multimodal analytics dashboard for story detection and visualization". *Video Verification in the Fake News Era*, 2019, pp. 281–299. DOI: 10.1007/978-3-030-26752-0_10.

377. V. Schetinger, S. Di Bartolomeo, E. S. de Lima, C. Meinecke, and R. Rosa. "n Walks in the Fictional Woods". *arXiv preprint arXiv:2308.06266*, 2023.

378. M. Schich, C. Song, Y.-Y. Ahn, A. Mirsky, M. Martino, A.-L. Barabási, and D. Helbing. "A network framework of cultural history". *science* 345:6196, 2014, pp. 558–562.

379. A. Schlegel, P. C. Cabral, and J. Lüdtke. *"Die" Laute in Europa 2: Lauten, Gitarren, Mandolinen und Cistern*. Lute Corner, 2011.

380. M. Schlögl and K. Lejtovicz. "A Prosopographical Information System (APIS)." In: *BD*. 2017, pp. 53–58.

381. M. Schlögl, F. Windhager, E. Mayr, and M. Kaiser. *Biographische Informationssysteme (DPBs, Digital Knowledge Databases, Virtual Research Environments)*. Zenodo, 2019. DOI: 10.5281/zenodo.2593761. URL: https://doi.org/10.5281/zenodo.2593761.

382. F. Schmiedl and L. Klepacki. *Journal of Cultural Management and Cultural Policy / Zeitschrift für Kulturmanagement und Kulturpolitik* 9:2, 2023, pp. 53–84. DOI: doi:10.14361/zkmm-2023-0203. URL: https://doi.org/10.14361/zkmm-2023-0203.

383. P. Schmitz and L. Pearce. "Humanist-centric tools for big data: berkeley prosopography services". In: *Proceedings of the 2014 ACM symposium on Document engineering*. 2014, pp. 179–188.

384. Scholars' Lab. *Neatline - Plot your course in space and time*. URL: https://neatline.org/. Accessed: 2021-09-04.

385. Scholars' Lab at the University of Virginia Library. *Mapping the Catalogue of Ships*. URL: https://ships.lib.virginia.edu/neatline/show/iliad-book-2. Accessed: 2023-25-06.

386. C. Schott. "Design und Implementierung einer Schnittstelle zur interaktiven Präsentation von 3D-Szenen auf mobilen Geräten mittels Augmented Reality". MA thesis. Leipzig University, Leipzig, Germany, 2018.

387. S. Schreibman, R. Siemens, and J. Unsworth. "The digital humanities and humanities computing: An introduction". *A companion to digital humanities*, 2004, pp. xxiii–xxvii.

388. J. Schwabish. *What is Story*. URL: https://policyviz.com/2017/03/20/what-is-story/. Accessed: 2022-07-04. 2017.

389. S. Schwandt. "Geschichte visualisieren: Digitale Praktiken in der Geschichtswissenschaft als Praktiken der Wissenschaftsreflexion". In: *Digital History. Konzepte, Methoden und Kritiken Digitaler Geschichtswissenschaft*. 2022.

390. M. Schwarz. *Die Wiener Hofburg im Mittelalter. Von der Kastellburg bis zu den Anfängen der Kaiserresidenz*. Verlag der ÖAW, 2015.

391. E. Segel and J. Heer. "Narrative visualization: Telling stories with data". *IEEE Transactions on visualization and computer graphics* 16:6, 2010, pp. 1139–1148.

392. K. Seirafi, J. Ossmann, and C. Doppler. "Four Ways to Experience Augmented Reality at Museums". *Methis. Studia Humaniora Estonica* 22:27/28, 2021-12, pp. 244–259. DOI: 10.7592/methis.v22i27/28.18451.

393. K. Seirafi and F. Wiencek. "»Supersizing the Museum« Digital Outreach und die Erweiterung des Museums in seine Umgebung". In: *Museen der Zukunft: Trends und Herausforderungen eines innovationsorientierten Kulturmanagements*. Transcript Verlag, 2021, pp. 213–240. DOI: 10.1515/9783839448960-010.

394. D. Shakespear. "Interactive Genealogy Explorer: Visualization of Migration of Ancestors and Relatives." In: *BD*. 2015, pp. 94–100.

395. Shanti Interactive. *VisualEyes*. URL: http://www.viseyes.org/visualeyes/. Accessed: 2023-08-07.

396. D. Shemek, A. Guidazzoli, M. C. Liguori, G. Bellavia, D. De Luca, L. Verri, and S. Imboden. "Renaissance Remix. Isabella d'Este: Virtual Studiolo." *DHQ: Digital Humanities Quarterly* 12:4, 2018.

397. Shift Design, Inc. *Historypin*. URL: https://www.historypin.org/en/. Accessed: 2023-08-07.

398. B. Shneiderman. "The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations". In: *Proceedings., IEEE Symposium on Visual Languages*. IEEE. 1996, pp. 336–343.

399. Shorthand Pty Ltd. *Shorthand - The fastest way to create beautiful content*. URL: https://shorthand.com/. Accessed: 2023-06-02.

400. Sketchfab. *Sketchfab*. URL: http://sketchfab.com. Accessed: 2024-02-27.

401. A. Slingsby and E. v. Loon. “Visual Analytics for Exploring Changes in Biodiversity”. In: *Workshop on Visualisation in Environmental Sciences (EnvirVis)*. Ed. by O. Kolditz, K. Rink, and G. Scheuermann. The Eurographics Association, 2013. ISBN: 978-3-905674-54-5. DOI: 10.2312/PE.EnvirVis.EnvirVis13.071-075.

402. Smithsonian National Museum of Natural History. *Objects of Wonder*. URL: https://storymaps.arcgis.com/stories/e0651067fae54280b7de1b3e919381e9. Accessed: 2023-25-06.

403. Stefan Pullen. *Patterns in the life of Vincent van Gogh*. URL: https://vangogh.stefanpullen.com. Accessed: 2023-25-06.

404. M. Stefaner. *Worlds, not stories*. https://well-formed-data.net/archives/1027/worlds-not-stories. Accessed: 2022-07-04. 2014.

405. C. D. Stolper, B. Lee, N. Henry Riche, and J. Stasko. *Emerging and Recurring Data-Driven Storytelling Techniques: Analysis of a Curated Collection of Recent Stories*. Technical report MSR-TR-2016-14. Microsoft Research, 2016-04. URL: https://www.microsoft.com/en-us/research/publication/emerging-and-recurring-data-driven-storytelling-techniques-analysis-of-a-curated-collection-of-recent-stories/.

406. D. L. Strayer, M. E. Power, W. F. Fagan, S. T. A. Pickett, and J. BELNAP. “A Classification of Ecological Boundaries”. *BioScience* 53:8, 2003, p. 723. ISSN: 0036-8075. DOI: 10.1641/0006-3568(2003)053[0723:ACOEB]2.0.CO;2.

407. Süddeutsche Zeitung. *Das Verschwinden der Bäume*. URL: https://www.sueddeutsche.de/projekte/artikel/politik/rumaenien-holz-mafia-wald-baeume-umweltschutz-umweltzerstoerung-deforestation-inc-saniral-egger-hs-timber-kronospan-e559172/?reduced=true. Accessed: 2023-03-09.

408. N. Sultanum, F. Chevalier, Z. Bylinskii, and Z. Liu. “Leveraging Text-Chart Links to Support Authoring of Data-Driven Articles with VizFlow”. In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. CHI ’21. Association for Computing Machinery, Yokohama, Japan, 2021. ISBN: 9781450380966. DOI: 10.1145/3411764.3445354.

409. J. E. Summers. “What exactly is meant by the term “auralization?”” *The Journal of the Acoustical Society of America* 124:2, 2008, pp. 697–697.

410. G. Sun, R. Liang, H. Qu, and Y. Wu. “Embedding spatio-temporal information into maps by route-zooming”. *IEEE transactions on visualization and computer graphics* 23:5, 2016, pp. 1506–1519.

411. Sun, Albert. *Diary of a Food Tracker*. URL: https://www.nytimes.com/interactive/2015/11/17/health/wiredwell-food-diary-super-tracker.html. Accessed: 2024-02-27.

412. P. Svensson. “Beyond the big tent”. *Debates in the digital humanities* 36, 2012, p. 49.

413. Tableau Software Inc. *Tableau - Tableau helps people see and understand data*. URL: https://www.tableau.com/. Accessed: 2023-06-02.

414. M. Tamper, P. Leskinen, and E. Hyvönen. "Visualizing and analyzing networks of named entities in biographical dictionaries for digital humanities research". In: *International Conference on Computational Linguistics and Intelligent Text Processing*. Springer. 2019, pp. 199–214.
415. Tass. *When Napoleon Ventured East*. URL: https://1812.tass.ru/en. Accessed: 2021-09-04.
416. G. P. Telemann. *Ertönet bald herrlich ihr letzten Posaunen*. 1741. URL: https://opac.rism.info/rism/Record/rism450004254?id=450004254&View=rism.
417. A. Telenius. "Biodiversity information goes public: GBIF at your service". *Nordic Journal of Botany* 29:3, 2011, pp. 378–381.
418. W. Telesko. *Die Wiener Hofburg 1835–1918. Der Ausbau der Residenz vom Vormärz bis zum Ende des „Kaiserforums"*. Verlag der ÖAW, 2012.
419. The IUCN Red List of Threatened Species. *International Union for Conservation of Nature and Natural Resources (IUCN) Red List of Threatened Species*. (Retrieved 2022-03-31). 2022.
420. The IUCN Red List of Threatened Species. *International Union for Conservation of Nature and Natural Resources (IUCN) Red List of Threatened Species - Supporting Information*. (Retrieved 2022-03-31). 2022.
421. The IUCN Red List of Threatened Species. *The IUCN Red List of Threatened Species*. https://www.iucnredlist.org/en. (Retrieved 2022-03-31). 2022.
422. The Museum of Modern Art. *Object:Photo*. URL: https://www.moma.org/interactives/objectphoto/#map. Accessed: 2024-02-27.
423. The Open Knowledge Foundation. *Medieval Philosophers*. URL: http://timemapper.okfnlabs.org/okfn/medieval-philosophers. Accessed: 2023-25-06.
424. ThingLink. *ThingLink - Create unique experiences with interactive images, videos & 360° media*. URL: https://www.thinglink.com/. Accessed: 2023-06-02.
425. A. Thudt, J. Walny, C. Perin, F. Rajabiyazdi, L. MacDonald, D. Vardeleon, S. Greenberg, and S. Carpendale. "Assessing the readability of stacked graphs". In: *Proceedings of Graphics Interface Conference (GI)*. 2016.
426. *TimeMapper - Elegant timelines and maps created in seconds*. URL: http://timemapper.okfnlabs.org. Accessed: 2021-09-04.
427. C. Tong, R. Roberts, R. Borgo, S. Walton, R. S. Laramee, K. Wegba, A. Lu, Y. Wang, H. Qu, Q. Luo, et al. "Storytelling and visualization: An extended survey". *Information* 9:3, 2018, p. 65. DOI: 10.3390/info9030065.
428. E. R. Tufte. *The visual display of quantitative information*. 2nd ed. Graphics Press, Cheshire, CT, USA, 2001.
429. M. D. F. Udvardy. *A Classification of the Biogeographical Provinces of the World: Udvardy MDF. 1975.A classification ofthe biogeographical provinces of the world.Morges (Switzerland): International Union of Conservation of Nature and Natural Resources. IUCN Occasional Paper no. 18.* IUCN Occasional Paper No. 18, Morges (Switzerland), 1975.

430. UNESCO Intangible Cultural Heritage. *UNESCO - Dive into intangible cultural heritage!* en. https://ich.unesco.org/en/dive. (Retrieved 2022-03-31). 2022.

431. A. Urbinati, E. Burdisso, C. Mattutino, S. Vilella, A. Semeraro, G. Ruffo, C. Corti, S. DE MARTINO, E. Devecchi, E. Scarpa, et al. "Bridging Representation and Visualization in Prosopographic Research: A Case Study". In: *CEUR WORKSHOP PROCEEDINGS*. Sun SITE Central Europe, Technical University of Aachen. 2022, pp. 80–92.

432. D. Vagavolu, A. S. M. Venigalla, and S. Chimalakonda. "MuseumViz–Towards Visualizing Online Museum Collections". *arXiv preprint arXiv:2106.11897*, 2021.

433. K. Van Es and M. T. Schäfer. *The datafied society. Studying culture through data*. Amsterdam University Press, 2017.

434. G. Vasari. *The lives of the most excellent painters, sculptors, and architects*. Modern Library, 2007.

435. M. Vecco. "A definition of cultural heritage: From the tangible to the intangible". *Journal of cultural heritage* 11:3, 2010, pp. 321–324.

436. S. Venkatasamy, G. Khittoo, P. Nowbuth, and D. R. Vencatasamy. "Phylogenetic relationships based on morphology among the Diospyros (Ebenaceae) species endemic to the Mascarene Islands". *Botanical Journal of the Linnean Society* 150:3, 2006, pp. 307–313. ISSN: 0024-4074. DOI: 10.1111/j.1095-8339.2006.00474.x.

437. VinePair Inc. *How Wine Colonized The World*. URL: https://vinepair.com/wine-colonized-world-wine-history/#1. Accessed: 2023-25-06.

438. Vinod Kumar. *The Travels of Marco Polo | Narrative Cartography*. URL: https://www.behance.net/gallery/64983491/The-Travels-of-Marco-Polo-Narrative-Cartography. Accessed: 2023-25-06.

439. Vizrt. *Vizrt*. URL: https://www.vizrt.com/. Accessed: 2023-06-02.

440. Vizzuality. *Forest Monitoring, Land Use & Deforestation Trends | Global Forest Watch*. en. https://www.globalforestwatch.org/. (Retrieved 2022-03-31). 2022.

441. E. M. Von Hornbostel and C. Sachs. "Classification of musical instruments: Translated from the original german by anthony baines and klaus p. wachsmann". *The Galpin Society Journal*, 1961, pp. 3–29.

442. Vue. *The Progressive JavaScript Framework*. https://vuejs.org/. [accessed 10-July-2023].

443. P. B. Waite. "Invading privacies: Biography as history". *The Dalhousie Review*, 1990.

444. K. Wang, C. Li, and X. Zhou. "Complex Network Analysis Based on Politics of Northern Song Dynasty". In: *2019 6th International Conference on Dependable Systems and Their Applications (DSA)*. IEEE. 2020, pp. 475–479.

445. M. Q. Wang Baldonado, A. Woodruff, and A. Kuchinsky. "Guidelines for Using Multiple Views in Information Visualization". In: *Proceedings of the Working Conference on Advanced Visual Interfaces*. AVI '00. Association for Computing Machinery, Palermo, Italy, 2000, pp. 110–119. ISBN: 1581132522. DOI: 10.1145/345513.345271. URL: https://doi.org/10.1145/345513.345271.

446. A. Watts. “The myopic view of the world”. *Eastern Wisdom, Modern Life-Collected Talks 1969*, 1960.

447. C. Weaver. “Multidimensional data dissection using attribute relationship graphs”. In: *2010 IEEE Symposium on Visual Analytics Science and Technology*. IEEE. 2010, pp. 75–82.

448. Webalon Ltd. *Tiki-Toki - Online Timeline Maker*. URL: https://www.tiki-toki.com/. Accessed: 2023-06-02.

449. U. G. K. Wegst. “Wood for sound”. *American Journal of Botany* 93:10, 2006, pp. 1439–1448.

450. U. G. K. Wegst, S. Oberhoff, M. Weller, and M. F. Ashby. “Materials for violin bows”. *International Journal of Materials Research* 98:12, 2007, pp. 1230–1237. ISSN: 1862-5282. DOI: 10.3139/146.101580.

451. M. Welzig. *Die Wiener Hofburg seit 1918. Von der Residenz zum Museumsquartier*. Verlag der ÖAW, 2018.

452. M. Whitelaw. “Generous Interfaces for Digital Cultural Collections”. *Digital Humanities Quarterly* 9, 2015.

453. Wikimedia Commons. *File:Giovanni Battista Viotti by Ducarme.jpg — Wikimedia Commons, the free media repository*. [Online; accessed 5-May-2023]. 2020. URL: https://commons.wikimedia.org/w/index.php?title=File:Giovanni_Battista_Viotti_by_Ducarme.jpg&oldid=479574405.

454. W. Willett, J. Heer, and M. Agrawala. “Scented widgets: Improving navigation cues with embedded visualizations”. *IEEE Transactions on visualization and computer graphics* 13:6, 2007, pp. 1129–1136.

455. F. Windhager, E. Mayr, M. Schlögl, and M. Kaiser. “Visuelle Analyse und Kuratierung von Biographiedaten [Visual Analysis and Curation of Biography Data]”. In: *Digital History. Konzepte, Methoden und Kritiken Digitaler Geschichtswissenschaft*. deGruyter, 2022, forthcoming.

456. F. Windhager. *A Synoptic Visualization Framework for Artwork Collection Data and Artist Biographies*. Doctoral Thesis, University of Vienna, AT, 2021.

457. F. Windhager, P. Federico, S. Salisu, M. Schlögl, and E. Mayr. “A synoptic visualization framework for the multi-perspective study of biography and prosopography data”. In: *Proceedings of the 2nd IEEE VIS Workshop on Visualization for the Digital Humanities (VIS4DH’17), Phoenix, AZ, USA*. Vol. 2. 2017, p. 2017.

458. F. Windhager, P. Federico, G. Schreder, K. Glinka, M. Dörk, S. Miksch, and E. Mayr. “Visualization of cultural heritage collection data: State of the art and future challenges”. *IEEE transactions on visualization and computer graphics* 25:6, 2018, pp. 2311–2330.

459. F. Windhager and E. Mayr. “Mental Models and Visualization.” In: *Visualization Psychology*. Springer, 2023.

460. F. Windhager, E. Mayr, J. Liem, J. Kusnick, S. Jänicke, and A. Grebe. "Traveling with Albrecht Dürer - A Case Study for Uncertainty-Aware Biography Visualization". In: *Biographical Data in a Digital World 2022*. ZRC SAZU, 2024. DOI: 10.3986/9789610508120_9.

461. F. Windhager, E. Mayr, M. Schlögl, and M. Kaiser. "Visuelle Analyse und Kuratierung von Biographiedaten". In: *Digital History: Konzepte, Methoden und Kritiken Digitaler Geschichtswissenschaft*. de Gruyter, 2022, pp. 137–150. DOI: https://doi.org/10.1515/9783110757101-008.

462. F. Windhager, E. Mayr, G. Schreder, M. Smuc, P. Federico, and S. Miksch. "Reframing Cultural Heritage Collections in a Visualization Framework of Space-Time Cubes." In: *HistoInformatics@DH*. 2016, pp. 20–24.

463. F. Windhager, S. Salisu, J. Liem, and E. Mayr. "The Knowledge Graph as a Data Sculpture: Visualising Arts and Humanities Data with Maps, Graphs, and Sets over Time". en. In: *Geographical Research in the Digital Humanities*. Bielefeld University Press, 2024, pp. 113–134. DOI: 10.1515/9783839469187-007. (Visited on 03/01/2024).

464. F. Windhager, S. Salisu, and E. Mayr. "Exhibiting Uncertainty: Visualizing Data Quality Indicators for Cultural Collections". *Informatics* 6:3:29, 2019, pp. 1–16. DOI: 10.3390/informatics6030029.

465. C. Wittmann. *Tenorposaune in B*. 1785. URL: https://mimo-international.com/MIMO/doc/IFD/OAI_ULEI_M0001892.

466. M. Wohlfart and H. Hauser. "Story Telling for Presentation in Volume Visualization". In: *Proceedings of the 9th Joint Eurographics / IEEE VGTC Conference on Visualization*. EUROVIS'07. Eurographics Association, Norrköping, Sweden, 2007, pp. 91–98. ISBN: 9783905673456.

467. A. Wong. "The whole story, and then some:'digital storytelling'in evolving museum practice". *MW2015: Museums and the Web*, 2015.

468. World Conservation Monitoring Centre and Convention on International Trade in Endangered Species of Wild Fauna and Flora. *Checklist of CITES species*. https://checklist.cites.org/#/en. (Retrieved 2022-03-31). 2022.

469. L. Yang, X. Xu, X. Lan, Z. Liu, S. Guo, Y. Shi, H. Qu, and N. Cao. "A Design Space for Applying the Freytag's Pyramid Structure to Data Stories". *IEEE Transactions on Visualization and Computer Graphics* 28:1, 2022, pp. 922–932. DOI: 10.1109/TVCG.2021.3114774.

470. J. Yorke. *Into The Woods: How Stories Work and Why We Tell Them*. Penguin Books, 2013.

471. A. Z. Yu, K. Z. Hu, D. Jagdish, and C. A. Hidalgo. "Pantheon: visualizing historical cultural production". In: *2014 IEEE Conference on Visual Analytics Science and Technology (VAST)*. IEEE. 2014, pp. 289–290.

472. A. Yuan, A. Coenen, E. Reif, and D. Ippolito. "Wordcraft: story writing with large language models". In: *27th International Conference on Intelligent User Interfaces*. 2022, pp. 841–852.

473. H. Y. Zhang. "The Study on Application of Artificial Board Materials in Musical Instrument-Manufacturing Engineering". *Advanced Materials Research* 583, 2012, pp. 255–258. DOI: 10.4028/www.scientific.net/AMR.583.255.

474. X. Zhang, J. Blaas, C. Botha, P. Reischig, A. Bravin, and J. Dik. "Process for the 3D virtual reconstruction of a microcultural heritage artifact obtained by synchrotron radiation CT technology using open source and free software". *Journal of Cultural Heritage* 13:2, 2012, pp. 221–225.

475. J. Zhao, S. M. Drucker, D. Fisher, and D. Brinkman. "TimeSlice: Interactive faceted browsing of timeline data". In: *Proceedings of the International Working Conference on Advanced Visual Interfaces*. ACM. 2012, pp. 433–436.

476. B. Zheng and F. Sadlo. "On the visualization of hierarchical multivariate data". In: *2021 IEEE 14th Pacific Visualization Symposium (PacificVis)*. IEEE. 2021, pp. 136–145.

477. Q. Zhi, A. Ottley, and R. Metoyer. "Linking and layout: Exploring the integration of text and visualization in storytelling". *Computer Graphics Forum* 38, 2019, pp. 675–685.

478. S. L. Ziegler. "Open Data in Cultural Heritage Institutions: Can We Be Better Than Data Brokers?" *Digital Humanities Quarterl* 14:2, 2020.

479. C. Zuanni. "Object biographies in the digital age: documentation, life-histories, and data". *International Journal of Heritage Studies*, 2023, pp. 1–16.

480. J. M. van der Zwaan, M. van Meersbergen, A. Fokkens, S. Ter Braake, I. Leemans, E. Kuijpers, P. Vossen, and I. Maks. "Storyteller: Visualizing perspectives in digital humanities projects". In: *International Workshop on Computational History and Data-Driven Humanities*. Springer. 2016, pp. 78–90. DOI: 10.1007/978-3-319-46224-0_8.