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Narrative medical visualization to communicate disease data

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ABSTRACT

This paper explores narrative techniques combined with medical visualizations to tell data-driven stories about diseases for a general audience. The field of medical illustration uses narrative visualization through hand-crafted techniques to promote health literacy. However, data-driven narrative visualization has rarely been applied to medical data. We derived a template for creating stories about diseases and applied it to three selected diseases to demonstrate how narrative techniques could support visual communication and facilitate understanding of medical data. One of our main considerations is how interactive 3D anatomical models can be integrated into the story and whether this leads to compelling stories in which the users feel involved. A between-subject study with 90 participants suggests that the combination of a carefully designed narrative structure, the constant involvement of a specific patient, high-qualitative visualizations combined with easy-to-use interactions, are critical for an understandable story about diseases that would be remembered by participants.

1. Introduction

Medical visualization research to date has focused primarily on supporting physicians in diagnosis and treatment and-to a lesser extent-medical students, particularly for anatomy education. Medical data and research, however, is also interesting to non-experts who lack detailed medical knowledge [1]. They may be interested in associations between lifestyle and diseases, in understanding diseases, and in (new) treatment options. Non-expert audiences require different design and narrative choices to craft a clear, approachable, and understandable message [2]. Interactive medical visualization aiming at this type of audience requires easier-to-understand representations [3] than expert systems such as radiology workstations.

Narrative visualization combines storytelling techniques with interactive graphics to communicate scientific results to a general audience [4]. The data should be presented in a traceable progression that is both memorable and straightforward [5,6] to prevent misinforming. Ynnerman et al. [7] coined the term *exploranation* for merging exploratory visualizations that are traditionally made for experts with explanatory visualization techniques. While exploration supports visual knowledge acquisition for non-experts, it requires more guidance and automatically-generated content.

Data-driven storytelling involves a narrative that is either based on or contains data [8]. Often, the story includes visual data representations which are enriched by memorable illustrations and highlighting techniques [4]. While data-driven story telling has already been applied to the visualization of astronomy data [9,10], climate data [3], molecular data [11] and cell biology data [12], the same has not been true for medical data. Exceptions include epidemiological data, e.g., the COVID-19 dashboard by the New York Times.[1]

In this work, we combine interactive exploration of medical disease data, focusing on 3D models of human anatomy, with narrative visualization techniques for a general audience. In our initial concept for medical story telling [13], we identified three public subgroups: Patients with a direct link to a specific disease, relatives of a patient, and people interested in medicine. Since patient-specific communication poses special challenges w.r.t.

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[1] https://www.nytimes.com/interactive/2021/us/covid-cases.html

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0097-8493/

data preparation and visual presentation, we focus on presenting interactive stories to people interested in medical topics. Our goal was to present a first approach to the construction of data-driven medical stories about diseases, where we focus on structural and design-specific decisions and challenges in this process. Second, we aim to provide initial insights into the extent to which such stories increase the memorability of aspects shown, whether users feel involved in these stories, and whether this could have a positive impact on their own lifestyle. Third, this work aims to provide a basis for future investigation of more detailed storytelling and visualization aspects with regard to medical data communication.

To reach these goals, we present and evaluate a narrative template to communicate disease information in a compelling and understandable way, following an asynchronous storytelling approach, i.e., one without a narrator [14]. We focus on the suitability and arrangement of narrative techniques to tell stories about three common diseases that have preventable risk factors and thus are well-suited to improve health literacy. We conducted a between-subject study to compare our interactive data stories in a web-based implementation against a traditional web blog design. The results show that interactive medical stories increase the memorability of the presented content. In addition, participants enjoyed exploring the 3D visualizations and indicated that they learned something new. We used these insights to **derive a research agenda for narrative medical visualization** which is our main contribution. In addition we make the following more specific contributions:

- A seven stage template to structure medical disease stories.
- Storyboards for three diseases that are enriched with interactive medical data visualization.
- A user study underlining the value of narrative medical visualization in terms of memorability and engagement.

2. Narrative visualization

A general audience includes people with varying levels of expertise who differ in terms of age and culture [3]. Bringing scientific results to a general audience is challenging, as it "[...] is quite a different matter to compel attention and understanding in a diverse, hurried, skeptical population of readers than to communicate with an eager, familiar group of associates" [15].

Results from cognitive science show that embedding data in a narrative makes the data more exciting and memorable [10]. For this purpose, complex scientific results need to be reduced, summarized and generalized by means of simplified and understandable visualizations. Compromises have to be made in terms of accuracy and completeness, since showing too many details makes it difficult to convey a clear message [3]. While numerous works combine narrative techniques and information visualization [16,17], there is little research on combining scientific visualization with narratives [10]. An early attempt is described by Höhne [18], who pioneered the interactive exploration of volume data for a museum exhibition. We explain the basic ingredients of a data-driven story in Section 2.1 and summarize existing tools to author data-driven stories in Section 2.2.

2.1. Ingredients of a data-driven story

In general, a visual data story consists of four basic ingredients [19]. First, the **content** of the story must be defined by establishing a series of specific facts, called *story pieces*, that are supported by data [14]. These story pieces are visualized to convey important messages to the audience. Visualizations are complemented by additional *communication* and *highlighting* techniques, called *story elements*, such as labels, arrows, motion, audio, and textual explanations to clearly emphasize these messages and to avoid ambiguity [20,21]. The interplay between story elements is best understood when they are connected. Stolper et al. [22] found three methods to connect story elements: interaction, consistent colors, and animations. Animations accompanied with speech are valuable to communicate complex data, especially to present health information to people with low health literacy [23].

Second, one or more **narrative characters** have to be defined that articulate the goal of the story. These can either be real people or objects, e.g., anatomical structures or diseases, in medical story telling.

Third, the story needs a **conflict** that describes the challenges that the main characters must solve to achieve their goals. Regarding medical data, a conflict could be that the person has a disease but wants to recover.

Fourth, the story needs a **structure**. Typically, a story is divided into three or five acts that are framed within *Aristotle's tension arc* [24] which defines the full progression of the story. The story starts with a relatively quiet opening that *introduces* the main characters and the conflict. This is followed by a middle section where tension, conflict between characters, and narrative momentum build to a *climactic* peak. The last act is a *denouement*, where the conflict is resolved with the characters either succeeding or failing in achieving their goals.

Each act is divided into scenes, where transitions are needed between the scenes without disorienting the user [4]. The story pieces and scenes are typically arranged in a meaningful genre [4], e.g., a slideshow or annotated chart. The choice of genre depends on the data complexity, as well as the intended audience and medium. Moreover, a story path is needed describing the order of scenes. In addition to a strict path (linear story), there is the possibility to provide the user with several paths to choose from (elastic story) [4].

Hullman and Diakopoulos [21] examined how framing effects in narrative visualization are used to influence audience opinion. These framing effects group into rhetorical categories that affect different aspects of the visualization (data, visual representation, annotation, interactivity). Moreover, a story can be told in different ways, e.g., engaging or emotional, depending on author intent and audience. Bach et al. [25] described eighteen narrative design patterns for telling data stories. These works led to Edmond and Bednarz's categorical classification of narrative visualization based on the strength and persistence of traditional narrative structures [26].

2.2. Authoring tools for narrative visualization

With the increasing popularity and accessibility of narrative visualization through interactive authoring tools, Stolper et al. [22] have identified several common visual components in existing stories. In addition, Wohlfart and Hauser have developed authoring tools for generating interactive medical stories based on volume data [27]. However, medical data also includes other data types, e.g., non-spatial data, clinical images, 3D models, and flow data.

Creating a scientific story based on rich multimedia sources that include spatial and non-spatial data is often limited in scope. Existing authoring tools require familiarity and training in several different software applications. For non-spatial data visualization with standard charts, Amini et al. [28] explored data videos to design better tools for telling data stories using motion graphics. This research led to DataClips [29], a tool to author data-driven videos composed of information visualizations. While the authoring process should be supported by flexibility, iteration, and nonlinear story creation, many authoring tools, such as Ellipsis [30], Data Comics [31], Timeline Storyteller [32], and Calliope [33], focus on manual workflows and are limited to non-spatial, often linear stories.

Fig. 1. Seven-stage template for narrative medical visualization of disease data.

3. Narrative medical visualization concept

While there are many artistic media, e.g., cinematic videos and hand painted illustrations, used to communicate medical topics, our aim is to mainly present real data. Using real data enables also non-artists, such as researchers doing science communication, to create narrative visualizations. However, there is a lack of a sound understanding of how to communicate real medical data encoding anatomical relationships and diseases to a lay audience. Two main aspects of story telling are to engage the audience into the story and to maintain their interest. Since the use of 2D static visualization may be considered less engaging, interactive 3D models should be integrated [11]. However, the integration and usefulness of interactive 3D anatomical models in a medical data-driven story remain unexplored.

Therefore, we outline a concept for the enrichment of 2D and 3D interactive medical visualizations by narrative techniques so that users are able to easily understand, absorb, and interact with the underlying medical data. Our intended **communication goal** is to **inform people interested in medicine** about a disease with a focus on avoidable risk factors. These people come typically into contact with medical data either in museums or science centers or through Internet research or TV programs at home, where no specific doctor–patient connection exists. Like the Visualization Center in Norrköping [34], asynchronous storytelling, based on a touch display, could be used to interactively inform the user about diseases. While users at home would more likely use a tablet or their phone, larger interactive displays could be used in a science center or museum.

To demonstrate the potential of narrative medical visualization as a means to engage the general public, we first derive a template comprising potential stages of disease stories, as detailed in Section 3.1. To illustrate this template in practice, we selected three common diseases for story generation, discussed in Section 3.2. We subsequently explain the production of our storyboards in Section 3.3. We present these three medical stories in Section 3.4. Finally, we provide details about the realization of the interactive web-based disease stories in Section 3.5.

3.1. A template for narrative disease visualization

Many university hospitals, scientific institutes or online encyclopedias offer freely-accessible web blogs to inform a general audience about the development, diagnosis and treatment of various diseases. We analyzed a total of 30 freely-accessible web blogs for three selected diseases: Liver cancer,[2,3,4,5,6,7,8,9,10,11] brain aneurysm,[12,13,14,15,16,17,18,19,20,21] and pelvic fracture[22,23,24,25,26,27,28,29,30,31] according to their basic structure, as we have the same communication goal and want to address the same audience.

The majority of these blogs follow a similar structure. First, a short and understandable **disease definition** is provided, and **statistical aspects**, such as the annual incidence and age-related distribution between men and women, are described. Next, an **anatomical overview**, consisting of schematic illustrations, shows the location and function of the structures affected by the disease. This provides the baseline for understanding what is normal before introducing the disease itself. Next, typical **symptoms** are explained, usually as textual enumeration. Afterwards, the **diagnosis** is explained. This includes the explanation of frequently-used examination methods, e.g., MRI, as well as their reliability. Each diagnostic method is briefly summarized and possible implications for the patient are explained. The diagnosis is typically followed by an overview of possible **treatment options**. Therapeutic procedures are summarized, including treatment risks, and the associated chance of cure is estimated. Typically, 5-year **prognoses** are provided. Finally, **disease prevention** summarizes risk factors for the development. A distinction is usually made between *avoidable* and *congenital/genetic* risk factors. This concluding consideration serves as a call-to-action, and clarification that one's own behavior has an strong influence on the development of life-threatening disease. The reader should be encouraged to think about their own habits and to positively adapt their lifestyle.

Based on this analysis, we derived a sequence of seven stages forming a template (see Fig. 1) that can be used as a basic structure for applying narrative techniques to disease data.

2 www.medicalnewstoday.com/articles/172408
3 https://my.clevelandclinic.org/health/diseases/9418-liver-cancer
4 www.mayoclinic.org/diseases-conditions/liver-cancer/symptoms-causes/syc-20353659/
5 www.healthline.com/health/liver-cancer/
6 www.webmd.com/cancer/understanding-liver-cancer-basic-information/
7 www.cancer.org/cancer/liver-cancer/
8 www.cdc.gov/cancer/liver/index.htm/
9 www.liverfoundation.org/for-patients/about-the-liver/diseases-of-the-liver/liver-cancer/
10 www.cancerresearchuk.org/about-cancer/liver-cancer/
11 www.cancer.gov/types/liver/
12 www.aans.org/en/Patients/Neurosurgical-Conditions-and-Treatments/Cerebral-Aneurysm/
13 www.mayoclinic.org/diseases-conditions/brain-aneurysm/symptoms-causes/syc-20361483/
14 www.hopkinsmedicine.org/health/conditions-and-diseases/cerebral-aneurysm/
15 www.med.unc.edu/neurosurgery/services/aneurysms-treatment/
16 www.urmc.rochester.edu/encyclopedia/content.aspx?ContentTypeID=85&ContentID=P08772
17 www.hopkinsmedicine.org/neurology_neurosurgery/centers_clinics/cerebrovascular/conditions/aneurysms.html/
18 www.uptodate.com/contents/unruptured-intracranial-aneurysms/
19 www.msdmanuals.com/professional/neurologic-disorders/stroke/brain-aneurysms/
20 www.rch.org.au/kidsinfo/fact_sheets/Cerebral_Aneurysm/
21 https://medlineplus.gov/brainaneurysm.html
22 https://orthoinfo.aaos.org/en/diseases--conditions/pelvic-fractures/
23 www.physio-pedia.com/Pelvic_Fractures/
24 www.renoortho.com/specialties/center-for-fracture-trauma/pelvis-fracture/
25 www.msdmanuals.com/home/injuries-and-poisoning/fractures/pelvic-fractures
26 https://radiopaedia.org/articles/pelvic-fractures
27 www.amboss.com/us/knowledge/Pelvic_fracture
28 https://patient.info/bones-joints-muscles/pelvic-fractures-leaflet
29 www.hss.edu/conditions_pelvic-fractures-acetabular-fractures.asp
30 www.aftertrauma.org/injuries-to-the-pelvis/injuries-to-the-pelvis
31 www.winchesterhospital.org/health-library/article?id=100262

3.2. Selected disease examples

In selecting the example diseases, we have been guided by the basic structures of the human body which are visible in radiological image data: organs, vessels, and bones. We selected a disease for each structure that has avoidable risk factors to build up motivation within the story to change one's lifestyle to prevent the respective disease as best as possible. Furthermore, producing an understandable visualization of these diseases is challenging due to their anatomical complexity. For each disease, an anonymized patient data set was used, comprising different radiological data types, such as ultrasound, MRI, and CT images. Below, we outline our motivation for selecting these diseases and necessary data pre-processing.

Liver Cancer. We selected liver cancer as an organ disease. The number of liver cancer cases has doubled in the last 35 years [35]. Public interest in learning more about this disease is therefore likely to increase. Furthermore, a comprehensible visualization of liver cancer is challenging due to the necessary depiction of numerous surrounding structures, such as other organs and vessels, as well as the simultaneous representation of embedded surfaces, such as liver and tumors.

We used a data set of a patient with a stage 1 liver carcinoma provided by our clinical partners. Small and medium-sized tumors without lymph node involvement and metastases were discovered in the liver using ultrasound and CT Angiography (CTA). Due to the good general condition of the patient and the early stage of the tumors, they should be surgically removed. Based on the CTA data, the liver, the tumors, and surrounding structures, such as the heart and ribs, were segmented and transformed to 3D models using the software *HepaVision* [36].

Brain Aneurysms. For vessel diseases, we selected dilations of the brain vessels, called brain aneurysms, which bear the risk of rupture. From a visualization point of view, aneurysms are interesting because a rather small and often irregularly shaped object (aneurysm) has to be represented in a comprehensible way in a large confusing context (vascular tree in the brain).

We used a data set from Berg et al. [37], where a brain aneurysm was incidentally found during CTA. The vasculature was segmented using the pipeline by Mönch et al. [38] and converted into a volume grid. Computational fluid dynamics (CFD) simulations were used to calculate the blood flow [37]. The blood flow is depicted by particles traced in the flow field.

Pelvic Fracture. For bone-related diseases, we used pelvic fractures, which is a break in any of the bones that form the ring of bones at hip-level [39]. A pelvic fracture can result from a high-energy trauma, such as a car accident, or in elderly patients, from a minor trauma, such as a fall. The visualization of hip fractures is interesting because many surrounding structures must be clearly displayed based on volume data for which a suitable transfer function must be found.

We used a CT data set of a woman with a pelvic fracture including pre-operative and post-operative scans from the Osirix Dicom Image Library.[32] Using direct volume rendering (DVR), we generate videos and images to support our story. In addition, we provide interactive 3D scenes based on the Virtual Surgical Pelvis (VSP) model [40], which is in use as a virtual educational tool to teach pelvic anatomy [41]. The VSP consists of anatomical surface models based on expert segmentation of a cryosection data set. Selected VSP structures were embedded as interactive 3D models.

[32] https://www.osirix-viewer.com/resources/dicom-image-library/

3.3. Generating medical storyboards

Once we had decided on which diseases to treat in the narrative visualization, and after we had prepared the material as described in the previous paragraph, we developed a storyboard for each disease. A storyboard is the essential basis for the implementation of the story, specifying the sequence of the story as well as the layout of text, images and other visual elements. Therefore, a storyboard enables dialogue in the team (and with stakeholders) and outlines the next steps in production. We used *PowerPoint 365 MSO* to create the storyboards, as it offers all functionalities to design a prototypical data-driven medical story. PowerPoint is widely-used and broadly accessible and can be regarded a low-threshold software that requires little expert knowledge. If offers tools for layout, animation and transition and supports a multitude of file formats, such as images, videos and even 3D models.

3.4. Medical story design

The stages shown in Fig. 1 serve as the basic structure for designing all three medical stories. Thus, some scenes for the three diseases are very similar. To avoid redundancy, we use the example of liver cancer to demonstrate a complete design of a medical story. For the two remaining diseases, we focus our discussion on illustrating disease-specific aspects. We attached all created stories as supplemental material.

In each story, we extracted from the source data set only the necessary structures to tell our intended story, because broad audiences need visuals that are clear, easy to read, and informative, which involves a fair degree of simplification, i.e., abstraction from the raw source data [2]. Following the *framing by hiding data* pattern [25], e.g., within the 3D models only the most important structures are depicted while irrelevant structures are excluded, e.g., other abdominal organs in the liver scenario. Moreover, aesthetics are valuable for non-experts, as the visual appeal of an asset draws interest and attention [2]. We consider this aspect in the coloring of our models, and use of graphical elements and annotations to the models to draw attention to important facts and pieces of the story.

Story Ingredients. A visual data story consists of four basic ingredients: content, characters, conflict, and structure (recall Section 2). The *content* of our stories comprises the development, diagnosis and treatment of selected diseases, where the *main character* is a patient. Following Böttinger et al. [42] to make scenes "as simple as possible without risking scientific credibility", we extract as much information as possible from real medical image data to generate data-driven stories. Besides visual abstraction, easy-to-use interaction techniques that do not jeopardize scientific credibility are also necessary for creating clearly understandable scenes [2,43]. For enabling touch-based interaction, *we use interaction types that do not require a high degree of accuracy*. These include *single-touch gestures*, e.g., rotation around a predefined axis, and *familiar multi-touch gestures*, such as panning and zooming. Such interactions take advantage of user familiarity with everyday objects such as smartphones and tablet PCs. In addition, the whole content is read aloud as a *voice over* [23].

The *conflict* in our stories is described by a sick person whose goal is to become healthy. For the *structure*, we used *Aristotle's tension arc*, which divides the story into five acts, called *Freytag's Pyramid*: exposition, rising action, climax, falling action, denouement [24]. We chose a linear path as each stage builds on information introduced previously, which makes it easy to keep track of presented information. Since we want an interactive and multi-media environment for our stories, *slideshows* seemed most appropriate as the basic narrative genre to visually present a sequence of scenes. In principle, we could also use another genre for the story or parts of the story, such as comics. However, comics are heavily symbolic and abstracted from the data and this would, in our opinion, weaken the degree of reality of the data too much. Within the scenes, we often combine 2D/3D representations with textual descriptions arranged in the *partitioned poster style* to explain disease stages in a short and memorable way. Following the *structuring by revealing data* pattern [25], elements within a scene are revealed sequentially to avoid visual overload for the user.

For each stage, one or multiple slides are prepared as scenes. Within the scenes, other narrative genres such as the flow chart and the partitioned poster genre are used, where *long-form textual description* with *highlighted keywords* provides more details. Smooth transitions are defined between scenes, with the timeline of stages visible in each scene to let the users know where they are in the story. Below, we provide details for acts and scenes of the story.

Narrative paradox. While the narrative storytelling approach means that a story is a message, interactive storytelling gives the user more control to tell a story that fits them. This interactive approach may feel more exciting, but is also harder to control. This fact of mutual influence on the story, on the part of the author through the storyboard and on the part of the user through interaction, describes the narrative paradox [44]. However, this is key to the idea of patient-centered medicine and giving people a way to learn what interests them about a particular medical condition. Maybe a user has extensive knowledge of anatomy, but does not understand the mechanism of a disease. They can jump to the part of the story that is relevant to them, and explore the 3D space in detail through interactive mechanisms. Alternatively, they can follow the planned narrative without additional exploration and still learn something valuable. However, then they cannot adapt the content of the story to their own needs and prior knowledge.

The key is to decide for each situation who has control over the story and to balance the degree of freedom the user is allowed to ensure a meaningful flow of the story [45]. Wohlfart and Hauser [27] proposed two interaction schemes to address this issue. Either (1) the visualization is fully controlled by the author or the user or (2) the control is shared between the two parties involved (e.g., the author controls the rendering styles and the user controls the camera movement). In our stories, we integrated both schemes. On the one hand the author has full story control in many scenes but on the other hand the user is encouraged to interact with certain story ingredients, e.g., to explore 3D models. Here the user controls the camera, but the main rendering parameters are specified by the author.

3.4.1. First act: Exposition

In the exposition, the fictive patient is introduced to motivate the audience to watch and interact with the story, as well as to make the story relatable. This is followed by a short definition of the disease modeling the conflict. To capture the user's attention, we start with a fundamental question related to the disease, e.g., "Liver Cancer: How to get back to life?".

Patient Description. To protect the privacy of personal data, any introductory patient information is fictitious but still represents the profile of someone who might receive this diagnosis. The patient description is the first scene of each story and consists of an *image* and a *long-form textual description* of the patient case, see Fig. 2(A1). The patient image was chosen from Google image search results, where we selected an image representing a common demographic for the decease in question which was freely available under a permissive Creative Commons license.

Disease Definition. To model the conflict of having a disease, we introduce the affected patient's anatomy by an *interactive 3D model*, see Fig. 2(B1). We exclude visual representations of the disease at this act, e.g., 3D models of the tumors or unnecessary surrounding anatomy, to avoid overwhelming the user. Inspired by Garcia [46], statistical parameters of the disease are depicted as *information graphics* with *icons* to aid recognition and memorability. Via voice narration, the user is encouraged to rotate the model. Since free rotation of 3D objects is difficult to handle, we limit rotation around a vertical axis with a finger movement from left to right. We apply similar concepts to the other two stories.

3.4.2. Second act: Rising action

During the second act, the tension is heightened through interactive 3D models of healthy anatomy and the visual representation of symptoms via icons, which lead to the diagnosis.

Anatomy. Within the anatomy scenes, we describe the relevant anatomical background for understanding disease development. These facts include the location, importance, and function of the key anatomical structure(s), see Fig. 2 (C1, D1, and A2). First, an *automatic rotation* of the 3D liver model gives an overview of its anatomical shape. Following *familiar objects* and *object continuity* concepts, the story transitions to show anatomical context around the liver: *labeled 3D models* of the ribs, heart, and vasculature. Finally, we introduce the disease by super- or juxtaposing the pathology on the normal anatomy with a crossfade transition. For the liver cancer story, the surrounding structures *fade away* and the fully-opaque liver becomes *translucent* to reveal tumors within, see Fig. 2(A2).

A unique characteristic of the pelvis fracture story is the complex anatomy of the pelvis. In addition, we have pre- and post-operative data available, which makes it possible to show treatment effects on real data. To communicate these anatomical peculiarities and the treatment process, we combine *hotspots* (markings of anatomically interesting positions), *3D models*, and *DVR*, see Fig. 3. The user can interactively explore anatomical structures by clicking on the hotspots (A) by highlighting the corresponding anatomical name in the text description or clicking on a structure of interest.

Symptoms. Using the *partitioned poster* genre, a visual overview of typical symptoms is provided. For each symptom, we create an *icon*, see Fig. 2(B2). The use of icons as a graphic representation of the term, as opposed to purely text-based listings, aims to increase memorability [47].

In the aneurysm story, we differ from our general approach in a few points, as the focus lies on accidentally-detected aneurysms without symptoms. Treatment bears considerable risks, which can exceed natural rupture risk. Therefore, the aneurysm story communicates how rupture-prone aneurysms can be detected as shown in Fig. 4. The first scene shows a 3D aneurysm model representing an incidental finding (see Fig. 4(A)). An illustrative superimposed *magnifying glass* helps the user to quickly see the aneurysm in the complex vascular tree. Next, aneurysm rupture is shown *illustratively* (see Fig. 4(B)), because there is no data available that encodes the rupture event. Using *information graphics*, it should be made clear that a rupture occurs very rarely but is very dangerous. The information graphics are only indicated by a placeholder, as these would be similar to the graphics of the liver definition stage.

Diagnosis. This stage provides information about the diagnostic process comprising diagnostic questions and imaging modalities. Important questions for liver cancer include, e.g., the size and location of tumors as well as the exact tumor type. For this purpose, the 3D translucent liver model including the tumors is shown. The renderings of the tumors are enriched by *icons* to visually communicate the main aspect of each related question

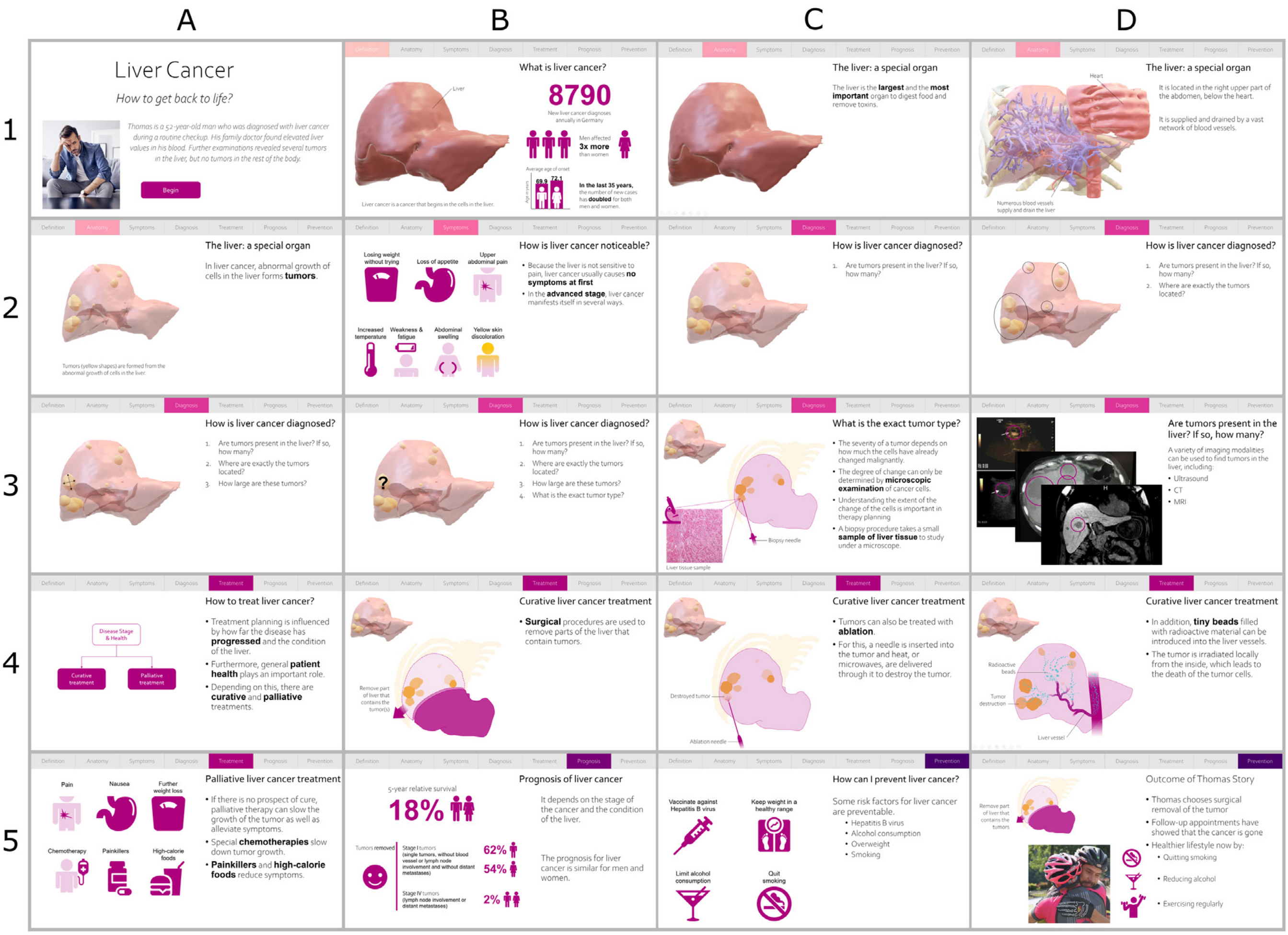


Fig. 2. All scenes of the liver cancer story covering the seven derived stages. The narrative sequence is A1, B1, …, D1, A2 and so on.

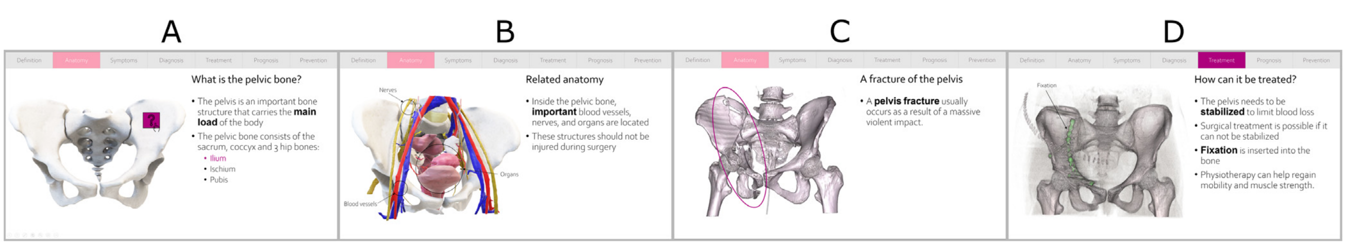


Fig. 3. Excerpts from the pelvic fracture story. A unique characteristic is the complex anatomy of the pelvis with multiple bones and closely related vessels, organs, and nerves. Hotspots, 3D models, and DVR are combined to highlight these aspects and treatment with a DVR model.

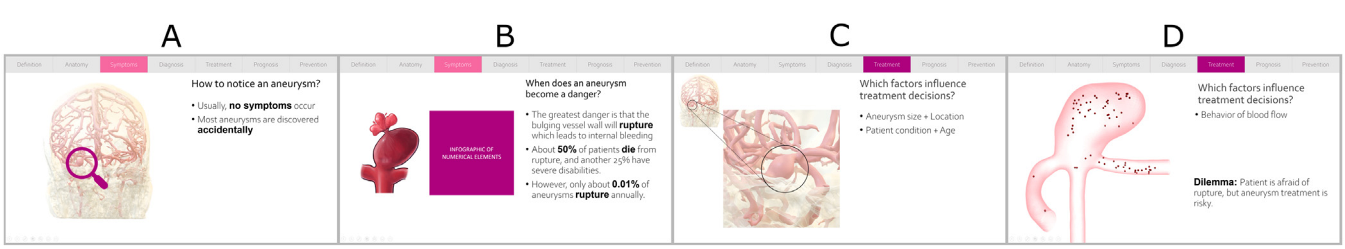


Fig. 4. Excerpts from the aneurysm storyboard. There is a trade-off between the rupture risk and the treatment risk. 3D models, concept-driven visualizations, and blood flow depictions are combined to communicate this dilemma.

(see Fig. 2(C2-B3)). Simple and clean *illustrations* subsequently describe diagnostic procedures, e.g., liver biopsy to determine the tumor type (see Fig. 2(C3)). Procedures with anatomical views include a *rotating 3D navigator model* of the organ that helps the user to maintain the orientation.

The size and location of aneurysms in the brain is also a critical diagnostic question, which we handle slightly differently since here a (branching) vascular tree represents the anatomical context instead of a large compact organ (see Fig. 4(C)). This entails beginning with a localizing *overall view* of the brain vessels with the translucent surrounding skull before a *zoom and rotation* transformation focuses the camera tightly on the aneurysm to emphasize its location and shape. *Panning and zooming* allows the user to get even closer to the aneurysm, a detail view is shown in the form of a 3D aneurysm model, with blood flow suggested by *animated particles*, see Fig. 4(D).

Additional scenes show diagnostic imaging modalities used. For each modality, a *real image* is incorporated as an example, e.g., ultrasound, CT, and MRI in liver cancer, where in each the tumors are highlighted by contours, see Fig. 2(D3).

3.4.3. Third act: Climax

The diagnosis led to the questions whether and how the disease can be treated, which is the climax of the story. Here, potential solutions for the conflict of being ill are presented, as described at the beginning of the story.

Treatment. This stage answers the question whether treatment is possible and explains therapy options and key aspects that influence treatment decisions. Rarely-performed treatments are not considered to avoid an excessive length of the story.

The first treatment scene uses a *flow chart* in the form of a directed graph, to describe the basic treatment approaches and their key aspects. In liver cancer there are essentially two treatment strategies: curative and palliative [48] (see Fig. 2(A4)). By clicking on one of the nodes, the user can start a *slide show* about the selected treatment. Each curative treatment is shown as a *2D illustration* of its key moment to provide clarity (Fig. 2(B4-D4)). We again use a *navigator icon* with *labels* to indicate key aspects of the procedure. An exception to this are the metal implants used in fracture treatment, such as in the pelvic data (see Fig. 3(D)). Similar to bones in a CT scan, these can be easily visualized by DVR, where optimal views from different perspectives can be shown. In case of palliative treatments where the aim is to ensure symptom alleviation, we use *icons* to create consistency and repetition between this stage and the earlier symptom stage (see Fig. 2(A5)).

3.4.4. Fourth act: Falling action

In the fourth act, the tension decreases by discussing the prognosis of treatment options as well as disease prevention focused on avoidable risk factors.

Prognosis. The prognosis of a disease includes several parameters related to the severity and the chosen treatment. Since a detailed presentation of all dependencies and resulting parameters would overwhelm the user, we limit ourselves to the most important parameters to give insight into the likelihood of a cure. Based on the *partitioned poster* genre, we produce an *infographic-style illustration* that makes use of *color* and *laddered text* to aid in information absorption and memory retention of key prognostic information (see Fig. 2(B5)). We use *icons* for men and women to convey that, unlike incidence, there are no significant prognostic differences between men and women. With this decision we follow the *concretization* and *personalization* pattern recommended by Bach et al. [25].

Prevention. In this stage, we focus on illustrating avoidable risk factors to give the user a sense of agency. Risk factors, such as age or genetic factors that a person cannot influence, are excluded since they are not actionable for the user. Similar to the symptoms, we use the *partitioned poster* genre and utilize *icons* to better recognize and understand the presented information, e.g., a martini glass for the recommendation to reduce alcohol consumption (Fig. 2(C5)).

3.4.5. Fifth act: Denouement

In the fifth act, the tension is resolved with a summary of the outcome of the fictitious patient story.

Outcome of Patient Story. To round off the story, we resolve the conflict. We once again show the *visualization* of the chosen treatment method to outline a concrete solution for conflict. In order to convey that liver cancer is not hopeless and one can make active efforts to prevent the disease, we decided to end the story on a positive note. For this purpose, we again show an *image of our fictional patient* (see Fig. 2(D5). Unlike at the beginning of the story, the patient has a joyful expression on his face and is exercising, which is an important preventive measure for liver cancer. We also list the *prevention options* the patient has taken to improve their lifestyle.

3.5. Realization of storyboards

Due to technological advances, web-based applications to visualize medical data have become increasingly important in recent years [49]. Web-based narratives can reach a wide audience easily. Therefore, we transformed the storyboard for liver cancer into an interactive web-based story.

To implement the principal structure of the web-based story, we used HTML5 and JavaScript. We used WebGL for interactive rendering of the 3D models. In addition to the script files for building the web interface, the GLTF files of the 3D models, the 2D illustrations as well as the sound files are stored on a university internal web server. The web server that only allows encrypted connections is managed by the university computer center. In addition, all radiological images and extracted models on the server are anonymized. Within the web application, JavaScript is used to read the GLTF files of the 3D models.

4. Evaluation

Our goal with this evaluation was to investigate if people interested in medicine are able to understand and remember our stories and whether they are engaged and motivated by them. We also derived factors that contributed to the user's engagement and motivation from participant feedback. We conducted a qualitative exploratory study in which we compared one of the interactive stories to a classical web blog design we created based on health website content such as *WebMD* and *UpToDate*. Moreover, participants rated structural and visual elements of our interactive story based on a questionnaire.

4.1. Study design and participants

We conducted a between-subject study by splitting the participants into two groups, group 1 (G1) and group 2 (G2). Our focus was on G1, which performed a comprehensive user study based on the interactive story w.r.t. the narrative elements used. G2 performed a shorter user study based on the classical web blog design with only a subset of the questions G1 received. Since classical web blogs which inform about medical issues usually do not follow a story path, we restricted this study to assessing the memorability of the presented content. Both studies could be taken using different devices, e.g., a computer or mobile devices such as smartphones or tablets, to facilitate access to the study.

We used LimeSurvey to set up both studies. To recruit participants, we shared the survey with colleagues and acquaintances. We also recruited participants through the *abwork* platform, where the participants were compensated $3.00 for their time. We did not set specific requirements for education, background, or gender to obtain a sample that represented a general audience. In addition, the survey was completely anonymous and answers regarding one's own risk of disease are voluntary. Furthermore, the questionnaire was reviewed and approved by the responsible data protection officer of our university. To protect participant anonymity, the survey was sent to multiple participants at a time.

In total, we recruited 90 participants, 45 for G1 (interactive story) and 45 for G2 (standard web blog). G1 includes 25 women and 20 men, while G2 includes 37 women and 8 men. Each participant was asked to select an age range, resulting in the following distribution: G1/G2: 12/2 21–29 yr., 17/13 30–39 yr., 3/18 40–49 yr., 6/10 50–59 yr., and 5/2 60–69 yr. The participants had different levels of education (G1/G2: 27/25 high school or some college, 15/16 with a bachelor's degree, and 3/4 with masters degree or beyond) as well as different levels of medical knowledge (G1/G2: 1/2 very comprehensive, 8/10 rather comprehensive, 11/25 moderate, 13/7 rather limited, 12/1 very limited). Regarding visualizations, the majority of participants were very familiar with reading diagrams, e.g., bar chart or line chart (G1/G2: unknown for 0/0, rather unknown for 3/1, parts/parts for 6/2, rather known for 9/11, and well known for 27/31). Moreover, many participants were at least partially familiar with medical illustrations like in a textbook (G1/G2: 0/2 unknown, 15/5 rather unknown, 5/16 parts/parts, 15/19 rather known, and 10/5 well known) as well as medical images, such as MRI or CT images (G1/G2: 0/0 unknown, 11/6 rather unknown, 14/9 parts/parts, 12/20 rather known, and 8/10 well known). In contrast, the majority were barely familiar with 3D visualizations (G1/G2: 6/4 unknown, 17/12 rather unknown, 11/20 parts/parts, 6/6 rather known, and 5/3 well known) and had little experience interacting with them (G1/G2: 7/8 unknown, 18/11 rather unknown, 9/17 parts/parts, 6/6 rather known, and 5/3 well known). Most participants of G1 used a PC/laptop without touch display for interacting with the story (G1/G2: 29/12), followed by PC/laptop with touch display (G1/G2: 8/3), as well as smartphone (G1/G2: 6/20) and tablet (G1/G2: 2/10). The different distribution of devices between both groups results from our recommendation to use a laptop or PC for G1, as the interactive story is currently optimized for it.

The study began with an introduction page, including a short greeting message, followed by descriptions on the purpose of the study, its duration (about 20 min), and expectations from the participants. For the interactive story group, we explained how to interact with the 3D visualizations. Participants were then directed to a new page showing either the interactive story or the web blog design. This page opened in a new browser tab, which made it easier for participants to return to the survey afterwards. After finishing the respective story, the participants were asked to fill out a short demographic questionnaire. Moreover, the participants were asked to answer multiple questions regarding nine main aspects of the story, using a five-point Likert scale, ranging from (1) do not agree at all to (5) fully agree. The following subsection describes the nine main aspects in more detail.

4.2. Study material and measures

For conducting G1 (interactive story), we employed the interactive liver cancer visualization, see Fig. 2, and for G2 (standard web blog) we developed a prototypical website based on the online-implementation of the liver cancer storyboard, see Fig. 5.

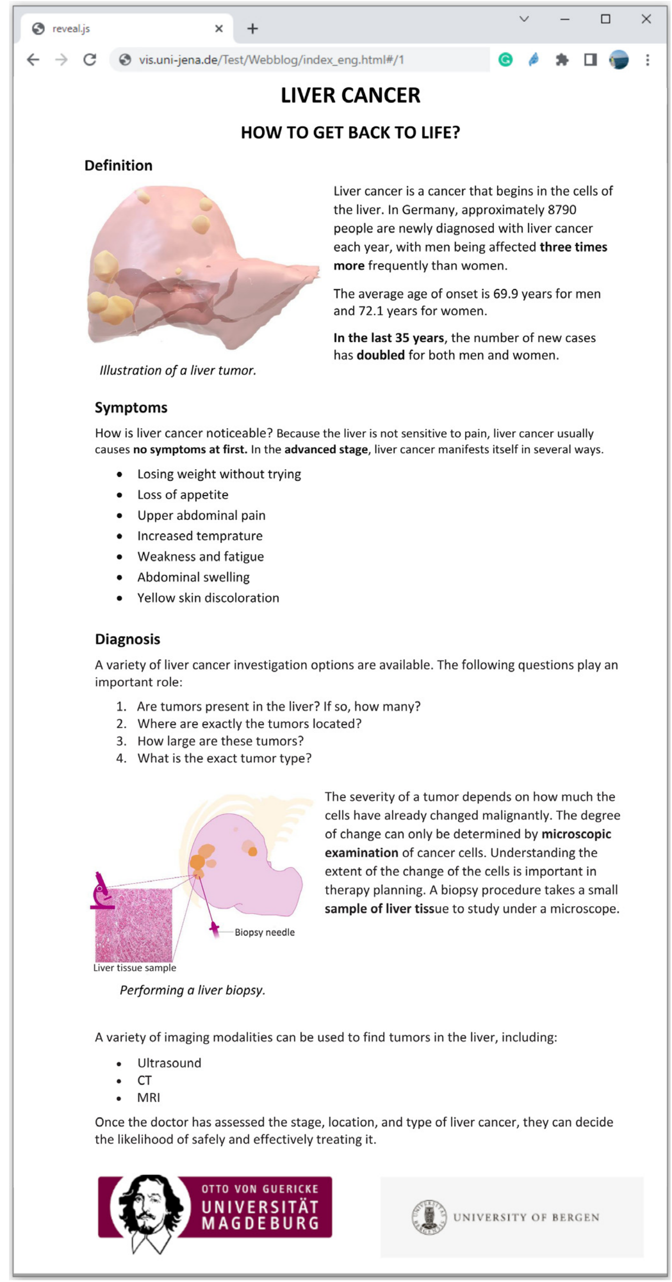


Fig. 5. Visual excerpts from the standard web blog design. A combination of text and 2D illustrations without voice over or other story ingredients to present the same content as in the interactive story.

Similar to existing medical web blogs, this summary combines text and 2D illustrations without voice over or other story ingredients. Thus, we ensured that both studies contained the same information.

Evaluation of narrative visualizations is a difficult task. The basic idea is to evaluate *design decisions made*, *techniques employed*, and *media used* in terms of aspects such as comprehensibility [50], memorability [51], and effectiveness in engaging a general audience [52,53]. For the selection of the main factors, we were guided by Borkin et al. [51] who investigated the memorability of visualizations, Dykes et al. [19] who researched the value of data credibility of narrative visualization, Garrison et al. [2] who emphasized the importance of appealing visualizations for non-experts, as well as, Amini et al. [53] who identified five factors of viewer engagement: cognitive and affective involvement, enjoyment, focused attention, and aesthetics. Moreover, we define risk perception as an important aspect for medical disease. The following main aspects were evaluated based on a questionnaire:

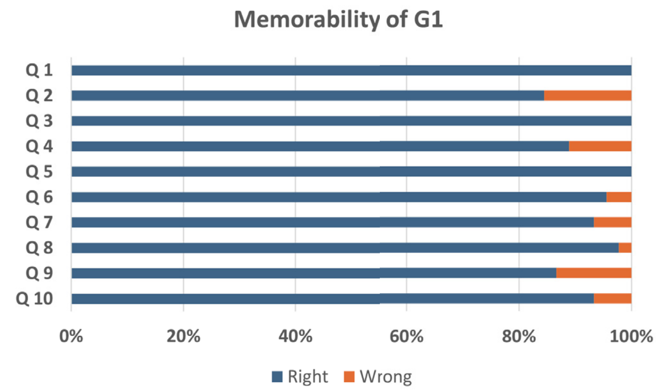
1. **Memorability** is an important goal of storytelling [51], which refers to the ability to preserve, maintain, or revive the thought of past events. For example, we asked participants which symptoms they remembered and which gender was more frequently affected.
2. **Cognitive involvement** addresses the interest in learning and reflecting on the information imparted. We asked the participants, e.g., if they found the content shown easy to understand and if they learned something new. The participants were asked to summarize the key messages of the story from their point of view.
3. **Affective involvement** describes the ability of the story to evoke emotions and deep feelings in the participant. Creating emotional connections to the story helps to retain the information [52].
4. **Enjoyment** is defined as a pleasurable affective response to a stimulus [53]. Example questions in this part include if the participants enjoyed watching the story and if they would recommend their friends to experience the story.
5. **Focused attention** describes the level of effort to concentrate on the story without being distracted. It is important that the story captures the attention of the participants so that they are motivated to follow with the story.
6. **Data credibility** is an important aspect for narrative visualization to convey to participants that the story is about real problems or issues [19]. With the currently increasing amount of data and misinformation, it is important to clearly communicate who the authors of a story are and where the underlying data comes from.
7. **Aesthetics** includes questions on whether the visualizations are visually appealing and understandable. Aesthetics is valuable for general audiences, as the visual appeal of an image draws interest and attention [2].
8. **Interaction** refers to the ability to interact with 3D anatomical models and if interaction in 3D helps to better understand the story content.
9. **Risk perception** summarizes what people took away from the story, in terms of their own risk for the disease presented. Participants were asked to voluntarily assess their risk of disease and indicate whether they would be willing to change their lifestyle. Increasing awareness of one's own risk factors is important to achieve the overall goal of improved health literacy through storytelling.

While participants of G1 had to answer all questions, those of G2 just had to answer the questions regarding the memorability. The complete survey including all questions of each factor is attached as supplemental material.

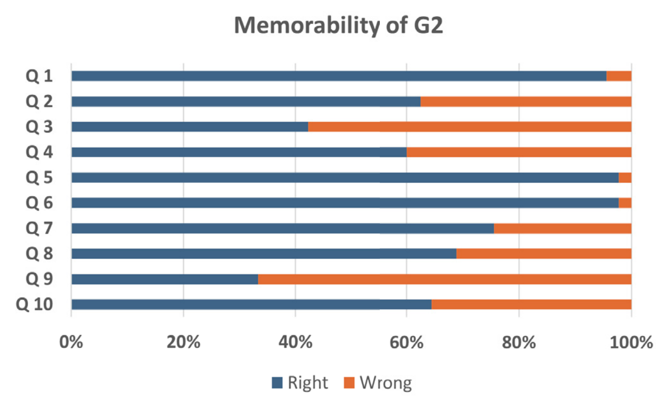
5. Results and discussion

In this section, we discuss the results of the user study regarding considered factors. Moreover, we discuss more general aspects of the medical story creation, such as template design and story ingredients. We also highlight take-away lessons, which we can conclude from the study results.

Memorability. We designed ten quiz questions to examine which facts the participants remember. The interactive story led to a higher number of correct answers compared to the traditional web blog design, see Fig. 6. The difficulty of the questions varied. For easier questions, e.g., "What disease was presented?" (Q1) or "What are the yellow structures inside the liver?" (Q2) (here, a screenshot was shown), the distribution of correct and incorrect answers were very similar between G1 and G2. More difficult questions related to categorical or numerical values presented in the story, e.g., "Who is more likely to be affected by liver cancer, men or women?" (Q3) or "What is the 5-year relative survival rate?" (Q9). For such questions, the interactive story achieved much better results. Similarly, participants of G1 could also recall more content, demonstrated in such questions as "What symptoms do you remember?" (Q6). Although participants of G2 named only one symptom (compared to two for G1) that did not appear in the story, participants of G2 were able to recall on median only two of the seven symptoms. Participants of G1 remembered a median of five symptoms. The reason for this is probably increased memorability by highlighting statistical facts through a combination of *sound*, *information graphics* with *icons*, and *textual designation*. In contrast, these facts were only textually highlighted in the web blog design, which seems to be quickly overlooked and forgotten. Therefore, we conclude that **encoding information across multiple sensory channels seems to support memorability**. However, we cannot infer from the results so far whether, e.g., the multi-sensory encoding, the interactive 3D models, or the navigation within the story, makes it possible to better memorize facts compared to the web blog layout.



(a)



(b)

Fig. 6. Results of the quiz questions for both groups, G1 (interactive story) and G2 (traditional web design) with 45 participants for each group.

Cognitive Involvement. The results regarding the cognitive involvement (Fig. 7(a)) show that many participants felt engaged in the story (Q11), where its structure (Q12) and content (Q13) were clear and easy to understand. Elements such as the **voice over**, **short text descriptions**, the **menu bar**, and the **interactive**

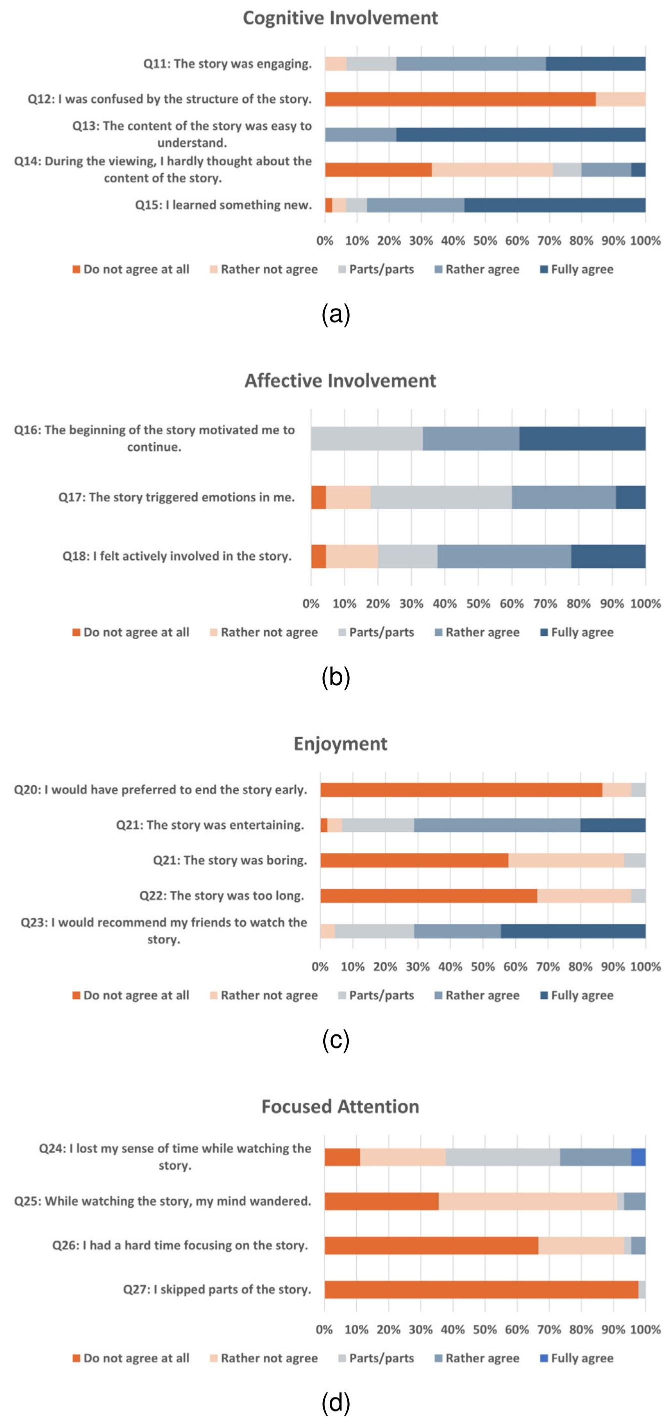


Fig. 7. Study results regarding cognitive involvement, affective involvement, enjoyment, and focused attention.

anatomical models were mentioned as influencing factors for an understandable story. When asked if any terms remained unclear after the story, only two participants of G1 indicated that the word "ablation" remained unclear. Thus, we assume that comprehensive storytelling benefits from a **combination of textual and verbal descriptions**. **Technical terms should be introduced in a way that they are easy to understand** and to identify, e.g., they could be highlighted throughout the story, offering a short dictionary-like explanation.

The majority of participants indicated that they learned something new through the story (Q15). In addition, two-thirds indicated that they "thought about the content of the story" during the viewing (Q14). Thus, we assume that the narrative visualization was successful in binding the undivided attention of the viewers. Concerning the key message, we can observe two groups: The first and larger group (36) stated the key message of the story was that a healthy lifestyle is important for the prevention of liver cancer. The remainder considered the story as an overview of liver cancer diagnosis. It is unclear if one of these groups is more likely to actually put the learnings into action by implementing life-style changes. Still, we assume that the story could be further expanded by a personal address. In this way, the story could close with a drop-down-selection of possible life-style changes, asking the participant to set an intention, e.g., "I will try to exercise more this week" or "I will try to eat less meat for a week".

Affective Involvement. While the beginning of the story with the introduction of the patient motivated participants to continue with the story (Q16) (Fig. 7(b)), users should be more involved in the story (Q18) to trigger more emotions (Q17), which in turn could help them remember the content and reconsider their own behavior. To achieve this, the **concrete patient case should be included more in the story**. So, e.g., by formulations such as "Thomas is one of 6.000 men who develop liver cancer". Or with the symptoms "as with most cases, Thomas' cancer went unnoticed at first. Only over time symptoms, such as abdominal pain, and weight loss developed". A relatable patient story could stimulate the viewer's sympathy for the patient's personal fate and awaken interest in how the story ends.

Enjoyment. Many participants found the interactive story a valuable way to learn about medical issues (Fig. 7(c)) and would recommend the story to their friends (Q23). Some participants missed explicit instructions that parts of the story can be skipped if the content is already known (Q22). These results underline the **importance of personalization**: allowing viewers to skip or watch parts of the story again accommodates for prior knowledge or personal interests. While the majority of participants found the story engaging, some indicated that the story could become more entertaining by animations, e.g., a transition from the outer liver wall to its interior to reveal the tumors (Q20). In conclusion, we cannot clearly deduce from the current results which elements or combination of elements contributed to the perception of the story as engaging. Individual participants gave verbal feedback, describing the interactive 3D models as particularly engaging. In the future, more specific user studies are needed to examine which elements make a narrative visualization engaging.

Focused Attention. In general, participants had no trouble focusing on the story (Q26) (Fig. 7(d)). However, their feedback included that the animations, e.g., of 3D models, should be better synchronized with the voice over. In addition, **interaction with the 3D models should not be possible during the explanations** to better focus on the content. Previously-mentioned techniques such as solving concrete tasks could also help participants lose their sense of time (Q24) and think less about other things (Q25).

Data credibility. To convey who the author of the story is and where the data came from, we showed logos of the universities involved at the beginning of the story. However, this is not enough to clearly show authorship and data origin (Fig. 8(a)). Participants indicated that in some cases the origin of the data (Q28) and who the author was (Q30) were not clear to them. To improve this, the **authors could be introduced at the beginning or at the end**. Furthermore, **videos and interviews with physicians could be included to disclose the origin of the data**. However, these aspects do not seem to have diminished confidence in the information conveyed. According to the comments, the **information**

shown seemed trustworthy to the majority (Q29), which was mainly **due to the clear structure of the story and the visually appealing visualizations**.

Aesthetics. Many of the participants found the depictions visually appealing and understandable, see Fig. 8(b). Regarding clinical image data, some participants with little prior experience with medical visualizations missed information on how these data are acquired. This could have been presented in optional story subpaths. Furthermore, **interactions based on the clinical images would increase their comprehensibility**. Accordingly, an ablation, for example, could be more easily understood through animation. Regarding the 3D models, some participants criticized their quality due to small segmentation errors in the form of holes, which in turn negatively influenced the rendering in some places. Also, during interaction, the text may overlap with the 3D models, making the labeling difficult to read. Thus, it is important to **use high quality models and smart labeling methods to avoid confusion and perception problems**. Moreover, some participants had perceptual problems when using a smartphone to view the story. The **stories should therefore be optimized for all devices and screen resolutions**. Specific studies are needed in the future to investigate the influence of animated 2D/3D illustrations as well as different rendering styles, e.g., illustrative vs. photo-realistic, on the understanding of the participants.

Interaction. It seemed clear to many participants how to interact with the 3D models (Q32) (Fig. 8(c)). However, the aforementioned quality issues and the lack of concrete tasks to be performed with the 3D models meant that some participants did not know why they should interact in 3D (Q33) and to what extent the interaction contributed to their understanding (Q31). Nevertheless, the majority had fun interacting in 3D (Q34). Moreover, while the majority enjoyed interacting in 3D, we cannot clearly assess whether interactive 3D scenes had a positive impact on story comprehension. This would have required **clearly defined interaction tasks**.

Risk perception. To test whether the story contributes to a change in the perception of one's own risk, we first asked which of the presented risk factors applied to the participants. A total of 18 participants reported having at least one of these risk factors (no hepatitis B vaccination: 3, overweight: 7, smoking: 8). Furthermore, participants were asked how high they considered their risk of developing liver cancer to be (very low: 13, rather low: 16, medium: 12, rather high: 3, very high: 0). Participants who stated that they did not have any of these risk factors consistently reported their risk as low to very low. In contrast, participants with risk factors, except three participants, rated their risk as medium to rather high. Finally, we asked whether participants would change their lifestyle. Sixteen participants who rated their risk as medium to rather high were more likely to agree that they would change their lifestyle. In addition, several participants who rated their risk as very or rather low also consider preventive measures. While these results show a positive influence of narrative representations on one's risk perception and willingness to adapt lifestyle, we cannot currently say which specific elements or content of the story lead to this positive influence.

Template design. Our presented template for the narrative presentation of disease data is based on layout and content structure of free health websites such as *WebMD* and *UpToDate*. Content on these websites was created in cooperation with clinical partners and is partly **based on physician's experience in patient education**. In the user study of the interactive story (G1), the structure and content were rated as understandable. However, we cannot deduce from the evaluation if the sequential structure of information is most appropriate for people interested in medicine, or if there are other, possibly better, structures.

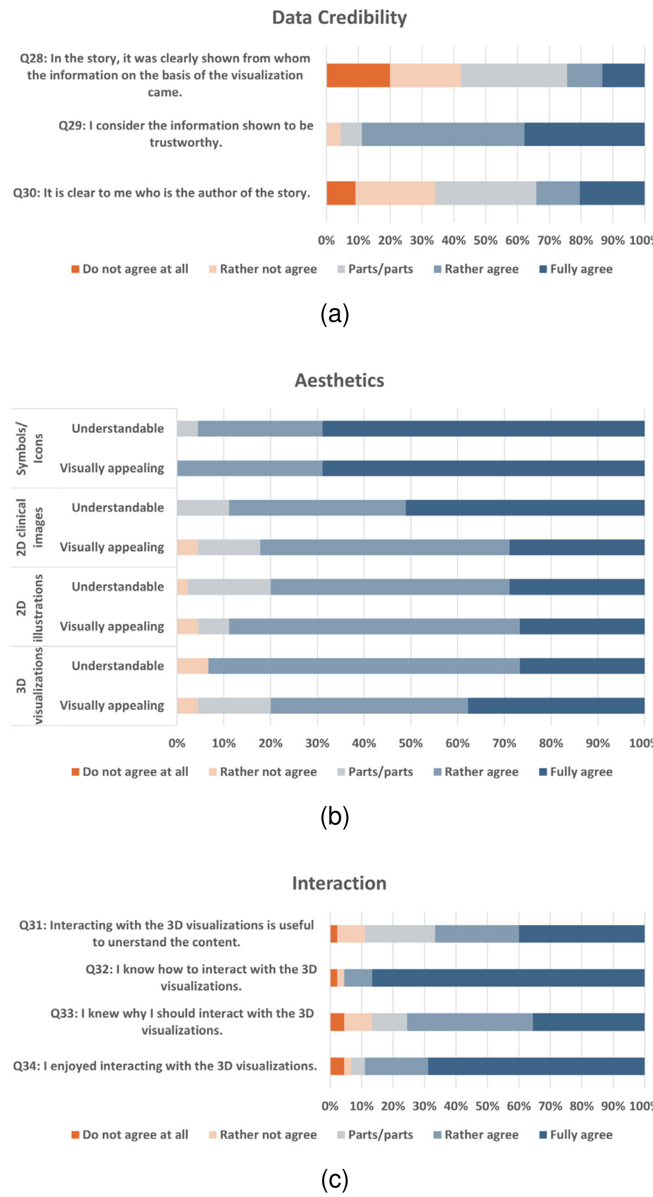


Fig. 8. Study results regarding data credibility, aesthetics, and interaction.

Therefore, we encourage future user studies to validate an optimal order depending on the audience. In addition, web blogs with a stronger focus on patient education sometimes use a finer distinction of the individual stages to show, e.g., the effects and consequences of early versus late treatment. Such sublevels could also be integrated into our template and presented to the user on-demand.

Our template focuses on diseases which can be diagnosed based on radiological images. The basic division into the seven stages can also be applied to other diseases, e.g., respiratory and infectious diseases, which are diagnosed by pulmonary function and blood tests, respectively. However, the media used must be adapted.

Story Ingredients. The conflict in the stories is described by a fictitious patient whose goal is to become healthy. However, we cannot yet say whether involving a single patient is the best option to tell a compelling story. Inspired by interactive documentary [54], **multiple patients and physicians**, e.g., in the form of interviews, **could be integrated** into the story **to**

familiarize the user with the story. While most users felt included in the story based on the conflict and *Aristotle's tension arc* chosen, the user study does not indicate whether other conflicts, e.g., an unknown present disease, as well as another tension arcs, e.g., a staircase tension arc [55] used in case a mystery should be solved, would be more appropriate. In addition to the main arc, smaller secondary tension arcs could be superimposed to express, e.g., feelings of individual characters [56].

There are currently no guidelines on which genre is most suitable for a given context. Since we used slideshows as the basic genre in all stories, we can currently not assess whether this genre is the best choice to represent a sequence of scenes. In order to evaluate genre influence, several variants of a story with different genres would have to be compared. The same applies to the use of design patterns [25]. While the design patterns we employed, such as *framing by hiding data* and *structuring by revealing data* as well as emotional (*concretize, humans-behind-the-dots*) and engaging (*call-to-action, exploration*) patterns seems to contribute to an engaging and memorable story, the influence of individual patterns on the story was not evaluated. In general, a validation and derivation of guidelines of contextual genre and design pattern recommendations is an important point for future research.

Narrative paradox. In the presented stories, both, the author and the user, control certain parts of the story. The resulting stories were perceived as engaging and understandable by the users. However, we cannot say whether the inclusion of other schemes, such as the *Martini Glass* structure [4], with a stronger focus on interaction, would have overwhelmed users or positively influenced comprehension.

6. Research agenda

This section focuses on open research challenges in particular on the combination of narrative techniques and medical data.

Authoring tools for narrative medical visualization. In this work the content production required significant manual effort. We used several external tools, including Adobe Illustrator[31] to produce icons and illustrations. In the future efficient authoring tools tailored to medical imaging data will be essential.

Game engines, such as Unity [57] or Unreal [58], offer a broad modular feature set for medical visualizations. These game engine modules could be extended with narrative modules to generate scenes. Key features should be interaction tracking, e.g., to create animations and the definition of which user interactions should be provided. Thus, advanced labeling [59] and animation creation [60] for medical data would need to be integrated. Moreover, machine learning techniques should be integrated to automatically arrange scene elements [61] and sequences of visualizations [62] optimally. In addition, efficient techniques are needed to generate medical illustrations. A solution could be to adapt and train a neural network that takes textual descriptions and a sketch of the desired output image as input and outputs an image of the requested scene.

Templates for medical data. The design of dedicated templates to capture medical narratives helps authors to structure their stories. In addition to our proposed template for disease data, there are many other medical concepts, such as healthy metabolic processes, pregnancy, and medical procedures. For these concepts, templates should be derived to structure such topics, possibly using our template as a starting point. Moreover, the templates should be programmable, which means that the story author can assign content to each scene within the template. This can be supported by an interactive story arc, where the author can easily arrange acts as well as adding scenes.

Narrative medical visualization for patients. Patients could also benefit from narrative medical visualization. They come into contact with medical data through their physicians, who explain planned procedures and diagnosed diseases as well as their prognosis. The patient typically sees excerpts from imaging data or schematic drawings on information sheets. However, since patients often have little medical knowledge, communication difficulties can occur, which could lead to uncertainty and fear. In a doctor–patient conversation, the patient could instead be informed about their condition using more personalized visualizations. The basis for this would be a story showing similar anatomical conditions to the patient. While the creation of an individual story for each patient would be too costly, the generation of representative example stories is feasible. Narrative visualization could help the patient to understand diagnostic and therapeutic procedures which would strengthen opportunities for participatory medicine.

Narrative medical visualization for experts. Narrative techniques could help medical students to understand complex medical data [63]. Depending on the learning objective, expert narratives can benefit from moderate abstraction regarding the visualization and underlying model [2]. An approach in this direction was recently presented by Linden et al. [64]. Using clustering and NLP approaches combined with time-line based visualizations, the most important information of a patient is extracted from electronic patient records. However, the visual processing of complex relationships of 3D models has not yet been considered. It would be interesting to further explore how expert tools can be enriched with narrative techniques and what impact this has on understanding.

Further evaluation of narrative medical visualization. Beyond our evaluation, there are many more design decisions that need to be evaluated, e.g., genres and narrative patterns. Moreover, there are different strategies to open a story, such as using a metaphor or just an image. It would be important to investigate which strategy works best in which case to open and end a story. For this purpose, structured and empirical studies are needed that compare different versions of a story.

Currently, we cannot say if the combination of our template with the Freytag's Pyramid is the best one to tell an exciting story that engages the user the most. A different order of the template stages would result in another story. It would be possible, e.g., to explain the patient's symptoms at the beginning and then reveal what disease the patient is suffering from and how it can be treated. Similarly, we could combine each act of the tension arc with one or more stages. At the moment, we use seven stages for the content that are assigned to five acts, but more or fewer stages per act would also be possible. We assume that a suitable number and sequence of template stages and their assignment to the acts depend on the narrative intent and target audience. In the future, the engagement of different story versions based on a varying number and order of stages need to be assessed. Between-subject studies could be conducted measuring how much time participants spend in each scene of the stories, how much they interact with the representations, and how much optional story paths are taken.

Moreover, stylizing 3D models with the aim to simplify and focus the attention on the important parts, needs to be evaluated. User studies are needed that evaluate different shading techniques to asses how accurate, informative, or useful they are. In addition, the suitability of further interaction options for exploring 3D models, such as setting cutting planes or windowing, need to be further investigated.

Advanced media for narrative medical visualization. In the last years new advances have been made in human–computer

[31] https://adobe.com/products/illustrator

interaction technology. Multi-touch displays have become very popular as they are intuitive, easy to use, and allow a direct manipulation of the visual data representation by multiple users. Also, VR environments are increasingly being developed for medical scenarios, such as surgical planning and medical education. It would be interesting to investigate how these media could be combined with narrative techniques to communicate medical data to general audiences.

7. Conclusion

The use of narrative techniques represents an important research focus with the goal of communicating complex scientific data in an understandable way to a general audience without specific expertise. To date, however, few approaches leverage narrative techniques for medical data, although the audience for this is large. Patients, relatives and people interested in medicine can benefit from custom medical representations and expand their knowledge. In addition, physicians and students could benefit from the use of narrative techniques.

In this paper, we demonstrate how narrative techniques could help explain diseases and treatment to a general audience. Our main contributions are the discussion and application of narrative design principles to different use cases to create interactive medical stories about diseases. While our conducted user study does not provide insight into which specific elements or interactions over the course of the story lead to improved understanding and recall, we can show that data-driven narrative stories generally improve recall of medical facts and increase personal risk perception. For users, the inclusion of interactive 3D anatomical models promotes entertainment, engagement and understanding. Drawing from the results of this study, we formulate a comprehensive research agenda. Important points for future research are the development of appropriate authoring tools and further evaluation of narrative medical stories.

CRediT authorship contribution statement

Monique Meuschke: Conceptualization, Methodology, Software, Visualization, Validation, Investigation, Writing – review & editing, Project administration. **Laura A. Garrison:** Conceptualization, Methodology, Resources, Writing – review & editing. **Noeska N. Smit:** Conceptualization, Resources, Writing – original draft preparation. **Benjamin Bach:** Writing – review & editing. **Sarah Mittenentzwei:** Conceptualization. **Veronika Weiß:** Conceptualization, Writing – review & editing. **Stefan Bruckner:** Funding acquisition, Validation, Writing – review & editing. **Kai Lawonn:** Supervision, Writing – review & editing, Funding acquisition. **Bernhard Preim:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.cag.2022.07.017.

References

[1] Lee B, Choe EK, Isenberg P, Marriott K, Stasko J. Reaching broader audiences with data visualization. IEEE Comput Graph Appl 2020;40(2):82–90.
[2] Garrison L, Meuschke M, Fairman J, Smit NN, Preim B, Bruckner S. An exploration of practice and preferences for the visual communication of biomedical processes. In: Eurographics Workshop on Visual Computing for Biology and Medicine. 2021.
[3] Böttinger M, Kostis H-N, Velez-Rojas M, Rheingans P, Ynnerman A. Reflections on visualization for broad audiences. In: Foundations of Data Visualization. Springer; 2020, p. 297–305.
[4] Segel E, Heer J. Narrative visualization: Telling stories with data. IEEE Trans Vis Comput Graphics 2010;16(6):1139–48.
[5] Figueiras A. Narrative visualization: A case study of how to incorporate narrative elements in existing visualizations. In: Proc. of Inf Vis Conf. 2014, p. 46–52.
[6] ElShafie SJ. Making science meaningful for broad audiences through stories. Integr Comp Biol 2018;58(6):1213–23.
[7] Ynnerman A, Löwgren J, Tibell L. Exploranation: A new science communication paradigm. IEEE Comput Graph Appl 2018;38(3):13–20.
[8] Riche NH, Hurter C, Diakopoulos N, Carpendale S. Data-driven storytelling. CRC Press; 2018.
[9] Bock A, Axelsson E, Costa J, Payne G, Acinapura M, Trakinski V, et al. OpenSpace: A system for astrographics. IEEE Trans Vis Comput Graphics 2019;26(1):633–42.
[10] Ma K-L, Liao I, Frazier J, Hauser H, Kostis H-N. Scientific storytelling using visualization. IEEE Comput Graph Appl 2011;32(1):12–9.
[11] Krone M, Schatz K, Hieronymus N, Müller C, Becher M, Barthelmes T, et al. From visualization research to public presentation-design and realization of a scientific exhibition. In: SIGRAD. 2017, p. 143–51.
[12] Höst GE, Schönborn KJ, Fröcklin H, Tibell LA. What biological visualizations do science center visitors prefer in an interactive touch table? Educ Sci 2018;8(4):166.
[13] Meuschke M, Garrison L, Smit N, Bruckner S, Lawonn K, Preim B. Towards narrative medical visualization. 2021, arXiv preprint arXiv:2108.05462.
[14] Lee B, Riche NH, Isenberg P, Carpendale S. More than telling a story: Transforming data into visually shared stories. IEEE Comput Graph Appl 2015;35(5):84–90.
[15] DiBiase D. Visualization in the earth sciences. Earth Miner Sci 1990;59(2):13–8.
[16] Tong C, Roberts R, Borgo R, Walton S, Laramee RS, et al. Storytelling and visualization: An extended survey. Information 2018;9(3):65.
[17] Gershon N, Page W. What storytelling can do for information visualization. Commun ACM 2001;44(8):31–7.
[18] Höhne KH. Virtual mummies - unwrapped by the click of a mouse. In: Mummies: Life After Death in Ancient Egypt. Prestel; 1997, p. 118–20.
[19] Dykes B. Effective Data Storytelling: How to Drive Change with Data, Narrative and Visuals. John Wiley & Sons; 2019.
[20] Kosara R, Mackinlay J. Storytelling: The next step for visualization. Computer 2013;46(5):44–50.
[21] Hullman J, Diakopoulos N. Visualization rhetoric: Framing effects in narrative visualization. IEEE Trans Vis Comput Graphics 2011;17(12):2231–40.
[22] Stolper CD, Lee B, Henry Riche N, Stasko J. Emerging and recurring data-driven storytelling techniques: Analysis of a curated collection of recent stories. Tech. Rep. MSR-TR-2016-14, 2016.
[23] Meppelink CS, van Weert JC, Haven CJ, Smit EG. The effectiveness of health animations in audiences with different health literacy levels: an experimental study. J Med Internet Res 2015;17(1):e3979.
[24] Madej KS. "Traditional narrative structure"–not traditional so why the norm? In: 5th Int. Conf. on Narrative and Interactive Learning Environments. 2008.
[25] Bach B, Stefaner M, Boy J, Drucker S, Bartram L, Wood J, et al. Narrative design patterns for data-driven storytelling. In: Data-Driven Storytelling. AK Peters/CRC Press; 2018, p. 107–33.
[26] Edmond C, Bednarz T. Three trajectories for narrative visualisation. Vis Inf 2021;5(2):26–40.
[27] Wohlfart M, Hauser H. Story telling for presentation in volume visualization. In: Proc. of Vis Conf. 2007, p. 91–8.
[28] Amini F, Henry Riche N, Lee B, Hurter C, Irani P. 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. 2015, p. 1459–68.

[29] Amini F, Riche NH, Lee B, Monroy-Hernandez A, Irani P. Authoring data-driven videos with dataclips. IEEE Trans Vis Comput Graphics 2016;23(1):501–10.
[30] Satyanarayan A, Heer J. Authoring narrative visualizations with ellipsis. Comput Graph Forum 2014;33(3):361–70.
[31] Zhao Z, Marr R, Elmqvist N. Data comics: Sequential art for data-driven storytelling. Tech. Report, Univ. of Maryland; 2015.
[32] Brehmer M, Lee B, Riche NH, Tittsworth D, Lytvynets K, Edge D, White C. Timeline storyteller: The design & deployment of an interactive authoring tool for expressive timeline narratives. In: Proc. of the Computation+ Journalism Symposium. 2, 2019.
[33] Shi D, Xu X, Sun F, Shi Y, Cao N. Calliope: Automatic visual data story generation from a spreadsheet. IEEE Trans Vis Comput Graphics 2021;27(2):453–63.
[34] Ynnerman A, Ljung P, Bock A. Reaching broad audiences from a science center or museum setting. In: Foundations of data visualization. Springer; 2020, p. 341–64.
[35] Liu Z, Jiang Y, Yuan H, Fang Q, Cai N, Suo C, Jin L, Zhang T, Chen X. The trends in incidence of primary liver cancer caused by specific etiologies: results from the Global Burden of Disease Study 2016 and implications for liver cancer prevention. J Hepatol 2019;70(4):674–83.
[36] Bourquain H, Schenk A, Link F, Preim B, Prause G, Peitgen H-O. HepaVision2—a software assistant for preoperative planning in living-related liver transplantation and oncologic liver surgery. In: CARS. 2002, p. 341–6.
[37] Berg P, Roloff C, Beuing O, Voss S, Sugiyama S-I, Aristokleous N, Anayiotos AS, Ashton N, Revell A, Bressloff NW, et al. The computational fluid dynamics rupture challenge 2013 – phase II: variability of hemodynamic simulations in two intracranial aneurysms. J Biomech Eng 2015;137(12):121008.
[38] Mönch T, Neugebauer M, Preim B. Optimization of vascular surface models for computational fluid dynamics and rapid prototyping. In: Int. workshop on digital engineering. 2011, p. 16–23.
[39] Gordon WT, Fleming ME, Johnson AE, Gurney J, Shackelford S, Stockinger ZT. Pelvic fracture care. Mil Med 2018;183(suppl2):115–7.
[40] Smit N, Lawonn K, Kraima A, DeRuiter M, Sokooti H, Bruckner S, et al. Pelvis: Atlas-based surgical planning for oncological pelvic surgery. IEEE Trans Vis Comput Graphics 2016;23(1):741–50.
[41] Smit N, Hofstede C-W, Kraima A, Jansma D, deRuiter M, Eisemann E, et al. The online anatomical human: web-based anatomy education. In: Proc. of annual conference of the european association for computer graphics: education papers. 2016, p. 37–40.
[42] Böttinger M, Kostis H-N, Ynnermann A. Challenges and open issues in visualization for broad audiences. In: Foundations of data visualization. Springer; 2020, p. 381–9.
[43] Viola I, Chen M, Isenberg T. Visual abstraction. In: Foundations of data visualization. Springer; 2020, p. 15–37.
[44] Aylett R. Narrative in virtual environments -towards emergent narrative. In: Papers from the AAAI fall symposion. AAAI Press; 1999, p. 83–6.
[45] Louchart S, Aylett R. Solving the narrative paradox in VEs–lessons from RPGs. In: Int. workshop on intelligent virtual agents. Springer; 2003, p. 244–8.
[46] Arcia A, Suero-Tejeda N, Bales ME, Merrill JA, Yoon S, Woollen J, et al. Sometimes more is more: iterative participatory design of infographics for engagement of community members with varying levels of health literacy. J Am Med Inform Assoc 2016;23(1):174–83.
[47] Haroz S, Kosara R, Franconeri SL. Isotype visualization: Working memory, performance, and engagement with pictographs. In: Proc. of the CHI. 2015, p. 1191–200.
[48] Anwanwan D, Singh SK, Singh S, Saikam V, Singh R. Challenges in liver cancer and possible treatment approaches. Biochim Biophys Acta Rev Cancer 2020;1873(1):188314.
[49] Preim B, Lawonn K. A survey of visual analytics for public health. 39, (1):2020, p. 543–80,
[50] Figueiras A. How to tell stories using visualization. In: Proc. of inf vis conf. 2014, p. 18–26.
[51] Borkin MA, Bylinskii Z, Kim NW, Bainbridge CM, Yeh CS, Borkin D, et al. Beyond memorability: Visualization recognition and recall. IEEE Trans Vis Comput Graphics 2015;22(1):519–28.
[52] Boy J, Detienne F, Fekete J-D. Can initial narrative VisualizationTechniques and storytelling help engage online-users with exploratory information visualizations. In: Proc. of the CHI. 2015, p. 18–23.
[53] Amini F, Riche NH, Lee B, Leboe-McGowan J, Irani P. Hooked on data videos: assessing the effect of animation and pictographs on viewer engagement. In: Proc. of Advanced Visual Interfaces. 2018, p. 1–9.
[54] Aufderheide P. Interactive documentaries: navigation and design. J Film Video 2015;67(3–4):69–78.
[55] Tobias RB. 20 MASTER plots: And how to build them. Penguin; 2011.
[56] Zagalo N, Barker A, Branco V. Story reaction structures to emotion detection. In: Proc. of the 1st ACM workshop on story representation, mechanism and context. 2004, p. 33–8.
[57] Nicoll B, Keogh B. The unity game engine and the circuits of cultural software. In: The unity game engine and the circuits of cultural software. Springer; 2019, p. 1–21.
[58] Sanders A. An introduction to unreal engine 4. CRC Press; 2016.
[59] Oeltze-Jafra S, Preim B. Survey of labeling techniques in medical visualizations. In: Proc. of EG VCBM. 2014, p. 199–208.
[60] Preim B, Meuschke M. A survey of medical animations. Comput Graph 2020;90:145–68.
[61] Wang Y, Sun Z, Zhang H, Cui W, Xu K, Ma X, et al. Datashot: Automatic generation of fact sheets from tabular data. IEEE Trans Vis Comput Graphics 2019;26(1):895–905.
[62] Kim Y, Wongsuphasawat K, Hullman J, Heer J. Graphscape: A model for automated reasoning about visualization similarity and sequencing. In: Proc. of the CHI. 2017, p. 2628–38.
[63] Rheingans P, Kostis H-N, Oemig PA, Robbins GB, Ynnerman A. Reaching broad audiences in an educational setting. In: Foundations of data visualization. Springer; 2020, p. 365–80.
[64] Linden Svd, van Wijk JJv, Funk M. Multiple scale visualization of electronic health records to support finding medical narratives. In: Proc. of EG VCBM. 2021, p. 113–22.