

# Accessibility of web-based data visualizations for people who are blind or visually impaired

DIPLOMARBEIT

zur Erlangung des akademischen Grades

**Diplom-Ingenieurin**

im Rahmen des Studiums

**Media and Human-Centered Computing**

eingereicht von

**Anne-Victoria Meyer**

Matrikelnummer 11741631

an der Fakultät für Informatik  
der Technischen Universität Wien

Betreuung: Univ.Prof.in Geraldine Fitzpatrick, PhD

Wien, 1. Mai 2023

---

Anne-Victoria Meyer

---

Geraldine Fitzpatrick



Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar  
The approved original version of this thesis is available in print at TU Wien Bibliothek.



# Accessibility of web-based data visualizations for people who are blind or visually impaired

DIPLOMA THESIS

submitted in partial fulfillment of the requirements for the degree of

**Diplom-Ingenieurin**

in

**Media and Human-Centered Computing**

by

**Anne-Victoria Meyer**

Registration Number 11741631

to the Faculty of Informatics  
at the TU Wien

Advisor: Univ.Prof.in Geraldine Fitzpatrick, PhD

Vienna, 1<sup>st</sup> May, 2023

---

Anne-Victoria Meyer

---

Geraldine Fitzpatrick



Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar  
The approved original version of this thesis is available in print at TU Wien Bibliothek.

# Erklärung zur Verfassung der Arbeit

Anne-Victoria Meyer

Hiermit erkläre ich, dass ich diese Arbeit selbständig verfasst habe, dass ich die verwendeten Quellen und Hilfsmittel vollständig angegeben habe und dass ich die Stellen der Arbeit – einschließlich Tabellen, Karten und Abbildungen –, die anderen Werken oder dem Internet im Wortlaut oder dem Sinn nach entnommen sind, auf jeden Fall unter Angabe der Quelle als Entlehnung kenntlich gemacht habe.

Wien, 1. Mai 2023

---

Anne-Victoria Meyer



Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar  
The approved original version of this thesis is available in print at TU Wien Bibliothek.

# Acknowledgements

This thesis would not have been possible without the support of many people that have helped me throughout the process. I am deeply grateful to everyone who has provided time, feedback, and support to help me while I was working on this thesis.

Firstly, I would like to thank my supervising professor Geraldine Fitzpatrick for providing never-ending support, helping me set the framing and the scope of the work, and providing feedback on my ideas, my plans, and my writing. I would also like to, specifically, thank her for helping me with finding contexts in which I can do focused thesis work.

Another person I would like to thank is Janis Lena Meißner, who has helped me with planning the study. I am also very grateful that she played the participant in a test run of the study and provided me with valuable feedback on how to improve the protocol for the sessions.

I would also like to express my gratitude to my five study participants, who helped me gain valuable insights. Some participants even went beyond the work that was required for study participation and provided me with additional feedback on my work. This is something I did not anticipate and that I am very grateful for. I would also like to thank Hilfgemeinschaft der Blinden und Sehschwachen Österreichs for helping me find the participants in the first place.

Lastly, I am eternally grateful to my friends and siblings, who have provided invaluable support to me throughout the process of working on this thesis. Thank you to everyone who has helped me make decisions about my work, who has given me feedback on my writing, who has volunteered to solve my visualization tasks, to everyone, who has been co-working with me, and to everyone, who has helped me stay sane in stressful times. More explicitly, I would like to express my deepest gratitude to my best friend, who has supported me in many ways throughout the entire time I was working on this thesis.



Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar  
The approved original version of this thesis is available in print at TU Wien Bibliothek.



# Kurzfassung

Datenvisualisierungen sind im Internet häufig anzutreffen, zum Beispiel in Nachrichtenartikeln oder in Daten-Dashboards. Diese Visualisierungen enthalten häufig Barrieren für Menschen mit Behinderungen, insbesondere für Menschen, die blind oder sehbehindert sind. Forschende haben gefordert, dass die Barrierefreiheit von Visualisierungen verbessert werden sollte. Diese Masterarbeit ist eine Antwort auf diese Forderung. Diese Arbeit beschäftigt sich mit der Frage, wie Wissen aus vorherigen Arbeiten genutzt werden kann, um web-basierte Datenvisualisierungen zu entwickeln, die für blinde und sehbehinderte Menschen besser zugänglich sind.

Um diese Frage zu bearbeiten, wurden drei Schritte unternommen: Zuerst wurden die Arbeiten anderer Forschender untersucht und bestehende Empfehlungen zur Barrierefreiheit web-basierter Datenvisualisierungen daraus extrahiert und synthetisiert. Das Ergebnis war eine Liste mit 19 Empfehlungen. Als zweiter Schritt wurde ein High-Fidelity-Prototyp in Form einer Webseite mit zwei Datenvisualisierungen entwickelt. Während der Entwicklung wurden die Empfehlungen beachtet. Der dritte Schritt war eine formative Evaluierung des Prototyps. Hierfür wurde eine Studie mit fünf blinden oder stark sehbehinderten Teilnehmenden durchgeführt. Die Studie bestand aus einem Aufgaben-Teil und einem Interview-Teil.

Die Teilnehmenden der Studie konnten die meisten Aufgaben mit dem Prototyp lösen und haben insgesamt positives Feedback zum Prototyp gegeben. Es hat sich auch gezeigt, welche Teile des Prototyps noch verbessert werden sollten.

Die Ergebnisse der Studie haben gezeigt, dass die Empfehlungen vorheriger Forschungsarbeiten sich in der Praxis als wertvoll erweisen. Der Prototyp war gut zugänglich für die untersuchte Gruppe. Es hat sich gezeigt, dass das Befolgen vieler Empfehlungen in der Praxis die Zugänglichkeit verbessert hat. Die Ergebnisse haben beispielsweise bestätigt, dass es wichtig ist, Visualisierungen auf verschiedene Arten und Weisen zugänglich zu machen, weil sich Benutzungspräferenzen individuell unterscheiden. Manchmal standen Präferenzen auch im Konflikt miteinander oder es wurden noch offene Probleme entdeckt. Dies sollte in zukünftigen Arbeiten genauer erforscht werden. Diese Masterarbeit leistet einen wissenschaftlichen Beitrag, indem sie drei Beiträge liefert: Eine synthetisierte Liste mit Empfehlungen zur Barrierefreiheit von Datenvisualisierungen, einen Prototyp als Beispiel für die Umsetzung der Empfehlungen und wertvolle Erkenntnisse aus einer Evaluierung des Prototyps mit blinden und sehbehinderten Menschen.



Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar  
The approved original version of this thesis is available in print at TU Wien Bibliothek.

# Abstract

Data visualizations are frequently encountered on the Internet, for instance in news articles or data dashboards. These visualizations often pose barriers to people with disabilities, especially to people who are blind or visually impaired. Researchers have demanded more research efforts to address the common lack of accessibility of visualizations. This thesis is one answer to this call for research. Specifically, it explores the question of how knowledge from previous works in this field can be used to create web-based data visualizations that are accessible to persons who are blind or visually impaired.

To explore this question, a methodology consisting of three parts was followed: As a first step, previous works were examined to extract and synthesize recommendations about the creation of accessible web-based data visualizations. This resulted in a list of 19 recommendations. As a second step, a high-fidelity prototype in the form of a website with two data visualizations was created. This prototype was developed according to the synthesized recommendations. In the third part, the prototype was assessed in a formative evaluation study. The study was conducted with five blind or visually impaired participants who were asked to solve tasks using the visualizations in the prototype. Afterward, they were asked about the accessibility of the prototype in a structured interview.

The participants of the study were able to solve most tasks using the prototype and generally gave positive feedback about the prototype. The study also revealed which parts of the prototype would need improvements.

The results of this thesis show that previous recommendations regarding visualization accessibility generally prove valuable in practice. The prototype turned out to be accessible to the studied group. Multiple recommendations from previous research were confirmed to improve accessibility in practice. The results, for instance, confirmed that it is important to include multiple ways to access the data since user preferences vary. The study also revealed some conflicting preferences and open issues, which should ideally be studied more closely in future research. This work contributes to the field of accessible visualizations by providing a synthesis of previous recommendations, an example implementation, and valuable insights from an evaluation with people who are blind or visually impaired.



Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar  
The approved original version of this thesis is available in print at TU Wien Bibliothek.

# Contents

<b>Kurzfassung</b>	<b>ix</b>
<b>Abstract</b>	<b>xi</b>
<b>Contents</b>	<b>xiii</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Research focus and contributions . . . . .	2
1.2 Structure of the thesis . . . . .	3
<b>2 Background and related work</b>	<b>5</b>
2.1 Background . . . . .	5
2.2 The lack of data visualization accessibility . . . . .	7
2.3 Diverse approaches for addressing the issue . . . . .	9
2.4 Approaches for accessible visualization development . . . . .	10
2.5 Addressing the gaps in previous research . . . . .	12
<b>3 Methodology</b>	<b>15</b>
3.1 Synthesis of existing recommendations . . . . .	15
3.2 Prototype development . . . . .	16
3.3 Evaluation of the prototype . . . . .	20
<b>4 Synthesized recommendations</b>	<b>27</b>
4.1 Synthesized recommendations . . . . .	27
4.2 Summary . . . . .	33
<b>5 The prototype</b>	<b>35</b>
5.1 Overview . . . . .	35
5.2 The bar chart . . . . .	39
5.3 The line chart . . . . .	39
5.4 Accessibility features . . . . .	40
5.5 Summary . . . . .	56
<b>6 Prototype evaluation results</b>	<b>57</b>
	xiii

6.1	Results of the tasks . . . . .	57
6.2	Results of the interview questions . . . . .	63
6.3	Additional observations and remarks . . . . .	68
6.4	Summary . . . . .	70
<b>7</b>	<b>Discussion</b>	<b>73</b>
7.1	Towards visualization accessibility . . . . .	74
7.2	Multiple ways for varying preferences and needs . . . . .	75
7.3	Providing a well-implemented table is key . . . . .	76
7.4	Textual descriptions are hard to get right . . . . .	76
7.5	Need for semantics and structure . . . . .	77
7.6	Sonification needs a clear concept . . . . .	79
7.7	Recommendations need to be practical . . . . .	79
<b>8</b>	<b>Conclusion</b>	<b>81</b>
8.1	Key contributions . . . . .	81
8.2	Limitations . . . . .	82
8.3	Future work . . . . .	83
	<b>List of Figures</b>	<b>85</b>
	<b>List of Tables</b>	<b>87</b>
	<b>List of Listings</b>	<b>89</b>
	<b>Bibliography</b>	<b>91</b>
	<b>Appendix</b>	<b>97</b>
A.1	Session protocol . . . . .	97
A.2	Base participant data . . . . .	99
A.3	Tasks (German original) . . . . .	99
A.4	Interview questions (German original) . . . . .	101
A.5	Interview questions (English translation) . . . . .	101
A.6	Further screenshots . . . . .	103

# Introduction

Imagine you open an article about the most recent developments of a global event, like the coronavirus pandemic. Beneath the title, before the article starts, you come across the following text:

*“26.02. 12.03. 26.03. 9.04. 23.04. 0 200 400 600 7-day moving average”*

You might be wondering what this is supposed to be. Maybe a mistake, perhaps the author of the article accidentally pasted something from a spreadsheet and then forgot to remove it before publishing the article.

What is shown above is a typical output a blind or visually impaired person might hear from their screen reader when encountering a data visualization on a website. Where one person will see a compelling chart with statistics about the development of the pandemic, another person will hear an incomprehensible string of dates and numbers without context.

Unfortunately, data visualizations on websites are frequently inaccessible to people who are blind or visually impaired. This inaccessibility can especially be observed when blind or visually impaired persons use screen reading software, that parses the content of the screen and reads it out to the user via text-to-speech. Often, visualizations are simply not detectable to screen readers, which makes them invisible to the user [SCWR21]. In other cases, as in the example above, parts of the visualization are recognized by the screen reader, but result in an output that is not comprehensible and not useful [SCWR21]. When closely examining the example text above, one might speculate that the dates at the start (“26.02. 12.03. 26.03. 9.04. 23.04”) are the tick marks of one axis of a chart and that the following numbers (“0 200 400 600”) are tick marks of the other axis. The text “7-day moving average” at the end might be a legend or a label of a data series in the chart. When we only hear or read the text, we can, however, only speculate what the visualization, from which this text originates, would look like.

Accessibility of data visualizations for people with disabilities is a topic that has previously been neglected by research [MLB<sup>+</sup>21, KJRK21, LCI<sup>+</sup>20]. However, recently

this field is seeing more research interest with different groups or researchers trying to address the issue from different angles [Elm23]. Some researchers [WTS19, WPA<sup>+</sup>21] have, for instance, started exploring how visualizations can be made more accessible to people with intellectual and developmental disabilities. Other researchers have studied the experiences of blind or visually impaired users with data visualizations [SCWR21, SFK<sup>+</sup>21]. Again another group [KJRK21] has critically examined the current state of the field and identified opportunities and challenges in this field.

This thesis seeks to make a contribution to the field of visualization accessibility by furthering the knowledge about how visualizations can be created so that they will be accessible to people who are blind or visually impaired. The focus of the research done in the scope of this thesis will be described in the next section.

### 1.1 Research focus and contributions

A typical place where data visualizations can be encountered are websites. Sharif et al. [SCWR21] have found in an empirical study that blind and visually impaired users face significant barriers when accessing these web-based data visualizations, as these visualizations are often either not detectable, incomprehensible or barely usable to them. Sharif et al. have called for more research on how web-based data visualizations can be made more accessible for people with disabilities. Since I am passionate about web technologies and have experience working as a web developer, I have taken this need for more research as an opportunity to focus on the accessibility of web-based visualizations in my thesis. This thesis is one contribution towards answering the call for more research in this specific area. The overarching question this work seeks to address is

*“How can we use the existing knowledge from previous research to create web-based visualizations that are accessible to persons who are blind or visually impaired?”.*

This question has been further split into three research questions that are addressed by different parts of this work and whose results together contribute to answering the overarching question. These questions and their resulting contributions are the following:

**RQ1: Which recommendations have been made by researchers with regards to creating web-based data visualizations that are accessible to blind and visually impaired persons?**

In order to build on the existing knowledge in the field, previous works were analyzed, and existing recommendations that can be applied to improve the accessibility of web-based data visualizations for blind or visually impaired persons were extracted and then synthesized. This part of the work contributes a list of 19 recommendations for creating web-based data visualizations that are accessible for people who are blind or visually impaired.



## **RQ2: How can these existing recommendations be translated into the design and implementation of a web-based data visualization?**

Building on the first contribution a prototype with web-based data visualizations was created. The 19 recommendations were followed and put into practice in the design and implementation of this prototype. This part contributes a high-fidelity prototype that exemplifies how current web technologies can be used to create data visualizations that are accessible to blind and visually impaired persons.

## **RQ3: Does a data visualization that is based on current accessibility recommendations prove usable and accessible to actual persons who are blind or visually impaired?**

A formative evaluation of the prototype was conducted in the form of a study with five blind or visually impaired persons. The study puts the prototype to the test by asking the participants to fulfill tasks with the prototype and by conducting a structured interview about the prototype after the tasks were finished. The study showed that the prototype was accessible and usable for the participants. The results of the study contribute on the one hand a confirmation of many recommendations regarding visualization accessibility and on the other hand point to some issues that need further research.

## **1.2 Structure of the thesis**

This thesis is structured in the following way:

- Chapter 1 motivates the need for researching visualization accessibility, defines the exact research questions that this work explores, and gives an overview of the structure of the thesis.
- Chapter 2 provides background information on blindness, visual impairment, and web accessibility and then discusses previous research in visualization accessibility.
- Chapter 3 describes the three parts of the methodology of this thesis: The synthesis of recommendations regarding visualization accessibility, the development of a prototype with visualizations, and the evaluation of the prototype with people who are blind or visually impaired.
- Chapter 4 lays out the recommendations that have been synthesized from previous works. These recommendations have been organized into 19 points.
- Chapter 5 gives a detailed description of the prototype and how the recommendations influenced the design and implementation of the visualizations.
- Chapter 6 describes the results from the evaluation of the prototype. This includes results from tasks that the participants carried out, feedback they gave, and observations that were made.

## 1. INTRODUCTION

---

- Chapter 7 discusses the results of chapters 4, 5, and 6, relates them to the research questions and previous literature, and lays out key insights gained from the work done in this thesis.
- Chapter 8 concludes the thesis by laying out the key contributions, pointing out the limitations of this work, and suggesting areas for future work.

# Background and related work

Researchers have stated that data visualization accessibility has previously not received enough attention from the research community [LCI<sup>+</sup>20] and have started demanding that more research efforts should be directed to this field [MLB<sup>+</sup>21, LCI<sup>+</sup>20]. Some work, however, has already been done in this field and research activity in this field is currently increasing [Elm23]. This chapter first provides some background information on blindness and visual impairment and then moves on to examine previous works in the field of visualization accessibility. The chapter concludes by identifying gaps in previous research and stating how this thesis seeks to address some of them.

## 2.1 Background

This section provides a general introduction to the topic of visual impairment and web accessibility for people who are blind or visually impaired.

### 2.1.1 Blindness and visual impairment

Before discussing accessibility for people who are blind or visually impaired, it should be clear, what blindness and visual impairment are. A person with *visual impairment* is defined by the American Optometric Association as follows:

*“Anyone with uncorrectable, reduced vision is visually impaired. Uncorrectable means vision that is not further improved by spectacles or contact lenses, it does not mean vision when not wearing glasses.” [Ass]*

Thus, anyone whose vision can be corrected using e.g. glasses is not included in the group of visually impaired people.

Vision impairment can be further divided into subcategories, depending on the level of impairment. In the International Classification of Diseases 11 (ICD-11) [WHO22] the

World Health Organization distinguishes the levels mild, moderate and severe vision impairment depending on the presenting visual acuity. Furthermore, people with visual impairments that exceed the criteria of severe vision impairment fall into the range of *blindness*. Blindness is then again subdivided in the ICD-11 according to the person's level of remaining vision. It is important to note here, that vision impairments and blindness are spectra and especially that not all people who are classified as blind have no vision at all. People who are blind can have different levels of usable remaining vision.

### 2.1.2 Internet use of people who are blind or visually impaired

People who are blind or visually impaired use different assistive technologies with their computers and phones to access websites. What technologies they use can depend on their type of visual impairment, as well as on other factors such as context. People who are visually impaired can use multiple assistive technologies together and also switch between them depending on their current activity and vision [SHZA16]. For instance, someone who is severely visually disabled might use magnification software on their computer and additionally turn on a screen reader, when their eyes get tired or when the magnification does not suffice for their current activity with the computer.

Which assistive technologies are used can also depend on social context, as some people who are visually impaired refrain from using some aids that would out them as having a disability in front of other persons [SHZA16].

**Screen reader** Many blind or visually impaired persons use a screen reader to access websites [LAKM07]. Screen readers are software programs that detect the structure and content of programs and websites and make them accessible to the user by outputting the content via speech or via a braille display. When the user opens a website the screen reader will read out the content of the website together with structural information about the content. For instance, a heading will be read out together with the information that this is a heading. The screen reader can also inform the user about what kind of regions, headings, and other structural elements are on a given website. The user can then choose to navigate to a specific part of the website directly e.g. by using a keyboard shortcut to jump through the headings or the images of a website.

**Refreshable braille display** Another assistive technology for blind or visually impaired persons are refreshable braille displays. Refreshable braille displays output content on a line or region of retractable pins that can be used to output text in the form of braille. A screen reader is necessary to use a refreshable braille display. The screen reader parses the content on the screen and relays relevant information to the braille display. For instance, when reading a table, the refreshable braille display might display the content of the currently focused row. It should be noted, however, that refreshable braille displays can be expensive [KJRK21] and are not frequently owned by blind or visually impaired persons.

**Magnification** Some visually impaired or blind persons who have some level of usable vision use digital magnification glasses or other mechanism for zooming the content of the screen. For instance, some magnification software allows the user to control an area that can be moved around the screen and that magnifies everything that is in that area. Some people also use settings of the browser or the operating system to enlarge everything or only the text. In a study by WebAIM [IfDRc] that surveyed users with low vision 48 % of participants stated that they use magnification and 44 % stated that they use the browsers zoom controls to zoom page content.

**High contrast mode** Another assistive technology used by blind and visually impaired persons are tools that let them change the colors and contrast of everything on their screen. This can usually be set up in the settings of the computer's or phone's operating system. Activating this mode forces the colors to be altered in a certain way. The user might, for instance, set up a theme with light text on dark background that forces all programs and websites to display content this way. However, how well this works also depends on how the programs and websites are implemented and how compatible they are with these high contract modes. A study of low vision users by WebAIM [IfDRc] found that 31 % of participants frequently use high contrast modes on their devices. Most of the high contrast mode users (71 %) stated that they use a color theme with light text on dark background.

### 2.1.3 Web accessibility

Web Accessibility means making web content accessible to people with disabilities. Web content needs to be designed and coded in specific ways so that is is usable by people with disabilities. For instance, images usually need a textual description that a screen reader can read out when the user comes across the image.

The World Wide Web Consortium (W3C) includes a group called the Web Accessibility Initiative which maintains guidelines for the creation of accessible web content. These are called the *Web Content Accessibility Guidelines (WCAG)* [W3C21]. The WCAG consist of a list of testable criteria that are organized in four sections according to the four underlying principles of accessibility: Perceivable, Operable, Understandable, Robust. These guidelines are the well-established standard for creating web content that is accessible to people with disabilities. The WCAG are usually used to assess the accessibility of websites and to identify accessibility issues. They are also used as a basis for accessibility laws in some countries [W3C23].

## 2.2 The lack of data visualization accessibility

Graphical content on websites is still frequently inaccessible to people who are blind or visually impaired. This is especially true for data visualizations [SCWR21]. Accessibility of data visualizations is something that has historically received too little attention. Multiple researchers have started pointing out the lack of work in this area [LCI+20,

[KJRK21]. In recent years an increase in interest and works in this area can be noted [Elm23]. This might be due to the general increase in interest in making technology more accessible to people with disabilities.

As accessibility of data visualizations on the web is still a field that has not sufficiently been explored, we don't yet have a comprehensive understanding of the experiences of persons with blindness or visual impairment with data visualizations on the web. However, some researchers have conducted studies to better understand the barriers that people with disabilities face when trying to access data visualizations on the web.

Siu et al. [SFK<sup>+</sup>21] conducted a mixed-methods study that found that data visualizations encountered on websites are frequently not accessible to people who are blind or visually impaired. They found that this hindered blind and visually impaired people from accessing data about the current developments of the COVID-19 pandemic, especially at the start of the pandemic. They found that especially local and global trend data about the progression of the pandemic was often not accessible.

Sharif et al. [SCWR21] conducted contextual interviews and an experiment with screen reader users who were blind or visually impaired to gain insight into the challenges screen reader users face with regards to data visualizations on the web. They found that visualizations were often not detectable by screen readers, thus making them completely inaccessible to the user. When they were detectable, they were frequently inaccessible. This means, that screen reader users knew that a data visualization was present, but were not provided with any comprehensible output when interacting with it using a screen reader, which frustrated the screen reader users. For instance, the screen reader would read out some numbers, but it would be unclear, what the numbers referred to. Another identified issue was that it was often not possible to explore the data in-depth e.g. by examining individual data points using a screen reader. Though, sometimes a data table was available, which enabled access to the data points.

Through the contextual interviews Sharif et al [SCWR21] found that screen reader users prefer to gain an overview of the data visualization first before further examining the details and individual data points. To gain a general understanding of the visualization screen reader users were looking for e.g. axis labels, maxima and minima, as well as global trends. Sharif et al. stated that this preference to gain an overview before drilling down is similar to how non-screen-reader-users interact with data visualizations.

Furthermore, Sharif et al. [SCWR21] found in their experiment that in comparison to participants not using a screen reader, screen reader users needed longer and were less successful in examining data visualizations and answering questions about the presented data. This was attributed to the accessibility issues of the data visualizations. This demonstrates how persons with blindness or visual impairment frequently lose time and miss out on possibly important information due to the inaccessibility of data visualizations on the web.

When Sharif et al. [SCWR21] compared the accessibility of data visualizations created using three different tools, they found that with the visualizations created using the libraries ChartJS and d3.js the participants did not have any access to the individual data points in the charts, which frustrated the participants.

## 2.3 Diverse approaches for addressing the issue

The inaccessibility of data visualizations is an issue that can be addressed from different angles. Therefore, previous works have demonstrated different approaches to making data visualizations more accessible. Some approaches focus on giving people with disabilities tools such as browser extensions to access the content of previously inaccessible visualizations on websites. Some approaches focus on creating tools and libraries that visualization creators can use to create accessible data visualizations. And then there are approaches that focus on developing guidelines techniques that can be used by visualization creators to create accessible visualizations using existing tools. This third approach is also what the work presented in this thesis focuses on. Nevertheless, a short overview of literature that takes the other approaches will be given here. Previous work that takes the chosen, third approach is discussed more in-depth in section 2.4.

**Tools for blind and visually impaired persons** Since many visualizations on the web are completely or partially inaccessible, researchers and professionals have worked on tools that enable blind and visually impaired persons to access the content of inaccessible data visualizations.

Some researchers are developing tools for blind and visually impaired persons that use image recognition technology to make visualizations accessible. Choi et al. [CJP+19] developed a tool that can parse raster images of visualizations, extract the data and use this to transform the visualization into a more accessible representation. They used their technique to develop a browser extension that interfaces with screen readers. This extension can be used by screen reader users to access visualizations stored in raster images that might otherwise be inaccessible to them. The extension makes the visualization available in the form of a text summary and a data table.

Kantharaj et al. [KLL+22] did similar work, that evaluated different models for automatically generating image descriptions from visualizations. They did not develop any concrete tool as Choi et al. [CJP+19] did, but instead focused on the models needed for generating the descriptions. They found that some models already yielded decent descriptions, however there were issues with factual errors in the descriptions and difficulty with accurately describing visual features such as trends.

There are also tools that blind or visually impaired persons can use to generate screen reader accessible visualizations from their own data. One example for this is the “Accessible Graphs” project [BSB] which offers a website with this functionality.

**Tools for creating accessible data visualizations** Some researchers have developed JavaScript libraries that can be used by web developers to create accessible data visualizations. An early example is the jQuery plugin evoGraphs [SF18] by Sharif and Forouraghi, which can be used to create bar charts and pie charts for websites. These charts then include an automatically generated description for screen reader users that describes the data in the chart.

A more recent example is the JavaScript library VoxLens [SWM<sup>+</sup>22] by Sharif et al. which can be used by web developers to make their data visualizations accessible. VoxLens improves the accessibility of the visualization by allowing users to interact with the data through different ways. VoxLens offers a textual description of the visualization, a sonification of the underlying data and a question-and-answer mode in which users can ask questions about the data in natural language.

Other researchers have developed tools that create accessible visualization files. For instance, Engel et al. [EMW19] have created a tool for creating accessible visualizations in the SVG format that can be used to create audio-tactile charts that can be used by blind and visually impaired people. They used web technologies such as HTML attributes and ARIA (Accessible Rich Internet Application) labels to make the visualization accessible by screen readers. The tool itself is accessible, too, and can be used to generate bar charts, line charts and scatter plots.

Serna-Marjanović et al. [SMTC20] have studied a tool for creating map visualizations to understand how accessibility is implemented in the resulting map visualization. This tool similarly also uses web technologies to make the resulting visualizations more accessible. They found that the visualization was navigable via keyboard, since all elements had `tabindex` attributes, which allowed them to receive keyboard focus, and a focus indicator, which highlighted the element that is currently focused. They also found that the visualization could be used with a screen reader since important information about elements was added via ARIA (Accessible Rich Internet Application) markup. Contrast of text and colors of visualization elements were also matching common accessibility guidelines.

### 2.4 Approaches for accessible visualization development

Some work has been done to develop guidelines and techniques for visualization creators that help them make their visualizations more accessible. The advantage of this approach is that it does not rely on specific tools or technology. For instance, the recommendation to include a table with the raw data can be put into practice regardless of what tools are used to create the visualization.

**Image descriptions** Some researchers have focused on image descriptions for data visualizations, that can be provided to screen reader users as an alternative to the visualization. Image descriptions are already commonly used on websites to provide an alternative for regular images such as e.g. photos. When the user navigates to an image, the screen reader announces that it is an image and reads out the image description. Since they are frequently used on websites, image descriptions are something that blind and visually impaired screen reader users will already be familiar with. However, researchers have pointed out, that currently there is no consensus yet on how data visualizations should best be described in natural language [KJRK21].

Lundgard and Satyanarayan [LS22] have started work on filling this gap by creating and evaluating a model for descriptions of data visualizations for screen reader users.



The model suggests that the text content visualization descriptions can be broken down into four levels. The levels of their model are: 1. “*Elemental and encoded properties*” e.g. descriptions of chart type and used encodings, 2. “*Statistical concepts and relations*” e.g. descriptive statistics such as minima and maxima, 3. “*Perceptual and cognitive phenomena*” e.g. visible trends and patterns, 4. “*Contextual and domain-specific insights*” e.g. additional context and explanations of the data. However, their evaluation did not yield a clear result about which levels would be the most useful and most important to include in visualization descriptions, as this varied between participants.

It should be noted however, that research by Siu et al [SFK<sup>+</sup>21] has shown that some blind and visually impaired users can be skeptical of image descriptions, as reading a description forces them to trust that the author of the description portrays the visualization accurately. These users would prefer not having to rely on someone else’s interpretation of the visualization.

**Guidelines and best practices** Another area that seems to lack more research is guidelines and best practices for creating accessible visualizations that can be used by a broad audience including people with disabilities [MLB<sup>+</sup>21]. When trying to create accessible data visualizations on the web could use the Web Content Accessibility Guidelines (WCAG) [W3C21] by the World Wide Web Consortium (W3C) to test and improve the accessibility of their visualizations. However, applying the WCAG guidelines to something like visualizations would not be a simple task, since there is little help in the WCAG about how accessible visualizations can actually be achieved.

One prominent resource in this area is Chartability [Ela21] by Frank Elavsky. Chartability provides a workbook with heuristics that can be used to test the accessibility of data visualizations. Its structure is based on the structure of the WCAG [W3C21]. Similarly to the WCAG the accessibility criteria are organized into broader principles. Chartability reused the four organizing principles from the WCAG “Perceivable”, “Operable”, “Understandable”, and “Robust” and complemented them with the three additional principles “Compromising”, “Assistive”, “Flexible”. Each principle has multiple testable criteria. For instance, one criteria within the “Understandable” section is “A title, summary, context, or caption must be provided.” [Ela21]. Chartability is a website with a downloadable workbook. The process of how Chartability was developed and a preliminary evaluation of it has also recently been described by Elavsky, Bennett and Moritz [EBM22]. Chartability is a valuable resource for testing the accessibility of data visualizations, but it does not offer a lot of guidance on how to achieve visualization accessibility during design and development. Many data visualization creators would like to have more practical guidance on how to make their visualizations accessible [JRG<sup>+</sup>22].

Similarly to Chartability, Alcaraz Martínez, Ribera Turró and Granollers Saltiveri [AMTGS21] have developed a set of 18 heuristics for testing the accessibility of charts for people who have low vision or a color vision deficiency. This work is also important, since especially the group of low vision users is often not addressed by research [KJRK21]. However, their heuristics are sometimes lacking clarity and sometimes overly specific in some details. They also have not been developed or evaluated with people with disabili-

ties. Nonetheless, this is an important start in developing guidelines for visualization accessibility for people who are visually impaired, but not blind.

There is still little work that offers actual recommendations and guidance on how to create data visualizations that are accessible to blind and visually impaired persons. One researcher who has started addressing this gap is Adam Strantz, who created a guide for using web technologies to create accessible visualizations [Str21b]. He included practical recommendations regarding various aspects of accessibility such as using semantic markup, labeling everything clearly and choosing accessible colors. The work of Strantz, however, is purely based on literature and the WCAG [W3C21] and so far no people with disabilities have been involved in creating or evaluating the guidelines.

Some studies have given a few design recommendations as outcome of their research. This has been done for instance by Kim et al. [KJRK21] who have analyzed previous research in the field of visualization accessibility. One part of their results was a model of a process in which visually impaired people could read data visualizations. This model consists of the four stages 1. “*Notifying the existence of a chart*”, 2. “*Providing an overview of the chart*”, 3. “*Offering details only when requested*” and 4. “*Conveying the context when necessary and helpful*” with some recommendations for how this process of interacting with the visualization can be supported in practice. Other works have conducted studies with blind and visually impaired persons and have also given some design recommendations as one outcome of their study. This has for instance explicitly been done by Sharif et al. [SCWR21] and more implicitly by Siu et al. [SFK+21].

### 2.5 Addressing the gaps in previous research

As described in this chapter, accessibility of web-based data visualizations is a field that is not well-researched yet, but that does currently experience an increased level of research activity. There have already been works [SFK+21, SCWR21], that examined the barriers that blind and visually impaired people face with data visualizations on websites. Researchers have taken different approaches to addressing these issues of inaccessibility. Some works have presented tools that blind and visually impaired people can use to make inaccessible visualizations more accessible [CJP+19]. Other works have experimented with JavaScript libraries [SF18, SWM+22] that web developers can use to create accessible visualizations. There have also been explorations into how textual descriptions for visualizations can be structured and which type of descriptions provide value [LS22].

Some researchers have started creating sets of heuristics for evaluating the accessibility of data visualizations [EBM22, AMTGS21]. These can be used to evaluate the accessibility of visualizations. However, it can be difficult to know how to design and implement visualizations so that they will be accessible and the heuristics often offer little guidance on how to create the visualizations in a way that they will pass the heuristic criteria. One work [Str21b] has started with providing practical recommendations to visualization creators. However, more work in this area is needed. Something that is also still missing are examples of implementations that demonstrate how the knowledge from previous

studies can be applied in practice. Another issue is, that most works developed the heuristics and recommendations purely from previous literature.

The work done in this thesis seeks to address these gaps in the current state of the field. For this reason, the following pieces of work were done to add to the knowledge in this area of research:

1. Create a set of recommendations for people who create web-based visualizations. These recommendations are based on results and recommendations of previous works and they don't come in the form of testable heuristics, but in the form of practical recommendations to practitioners.
2. Develop a prototype of an accessible web-based visualization that explores how the recommendations can be applied in practice.
3. Conduct an evaluation of the prototype with people who are blind or visually impaired to see whether following the recommendations helps in achieving data visualizations that are useful and usable to actual persons with disabilities.

The details of the methodology applied in this work are described in chapter 3.



Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar  
The approved original version of this thesis is available in print at TU Wien Bibliothek.

# Methodology

The methodology of this work consists of three steps that each answer a part of the overarching question of how existing knowledge can be used to create web-based data visualizations that are accessible to persons who are blind or visually impaired. The result of each step is a contribution in itself, but is also used as a basis for the following step. These are the three steps that were conducted for this work:

**Step 1: Synthesis of recommendations** Previous literature was examined in order to identify and synthesize recommendations regarding the accessibility of web-based data visualizations for persons who are blind or visually impaired. Details in section [3.1](#).

**Step 2: Prototype development** Based on the recommendations from step one, a prototype in the form of a website with two accessible data visualizations was developed. Details in section [3.2](#).

**Step 3: Evaluation of the prototype** The prototype was evaluated with five people who are blind or visually impaired. Details in section [3.3](#).

## 3.1 Synthesis of existing recommendations

This work seeks to explore the overarching question of how web-based data visualizations can be made more accessible for people who are blind or visually impaired. As a first step towards answering this question, existing literature in the field of accessible data visualization was analyzed in order to identify existing recommendations regarding the accessibility of web-based data visualizations for people who are blind or visually impaired. In order to identify and synthesize existing recommendations from the literature, the process described below was followed. The recommendations that resulted from this process are described in chapter [4](#).

1. **Literature search.** Literature on the accessibility of data visualizations was gathered through online research, mostly through keyword searches<sup>1</sup> on Google Scholar and through following citations of relevant works.
2. **Identification of relevant works.** The resulting works were closely reviewed and works that contain recommendations for creating accessible data visualizations were identified. The criteria for relevancy of works were: The recommendations need to refer to the accessibility of data visualizations. The recommendations need to be relevant to the accessibility for persons who are blind or visually impaired. The recommendations need to be applicable to web-based applications.
3. **Gathering of recommendations.** Each work was examined for recommendations according to the aforementioned criteria. The resulting recommendations were gathered in a list of excerpts from the literature.
4. **Derivation of preliminary recommendations.** From the excerpts a list of preliminary, rough recommendations was created.
5. **Grouping of preliminary recommendations.** Related preliminary recommendations were grouped. Each group was given a title. The first grouping of recommendations was not satisfactory yet. This is why it was undone and redone so that the resulting groups would be more logical.
6. **Categorization of excerpts.** The excerpts from the literature were then sorted into the groups from the previous step. If they fit into multiple groups, they were added to multiple groups. The preliminary recommendations were then removed since they only served as a stand-in for the actual excerpts.
7. **Synthesis within groups.** Within each group the excerpts from the literature were synthesized to produce concise recommendations. Conflicts in the recommendations from different sources were resolved or stated in the resulting text. The resulting recommendations are described in chapter 4.

## 3.2 Prototype development

To try out the implementation of the synthesized recommendations (see chapter 4) in practice, a high-fidelity prototype was implemented. This section gives an overview over the technology, data sets, accessibility testing and choice of diagram types behind the prototype. For a detailed description of the prototype itself, please refer to chapter 5. For the source code of the prototype and a link to the working prototype, refer to the project's GitHub repository<sup>2</sup>.

---

<sup>1</sup>Using combinations of keywords such as “data visualization”, “charts”, “diagrams” , “accessibility”, “accessible”, “assistive technology”, “blindness”, “visual impairment”, “low vision”, “guidelines”.

<sup>2</sup><https://github.com/Anne-Victoria/Accessible-Data-Viz-Prototype>

### 3.2.1 Goal

The prototype consists of two data visualizations that try to model how data visualizations can be made more accessible according to recommendations from the literature. The goal was to try out, how these rules and suggestions can be translated into practice and then to further evaluate in a study, whether the implemented recommendations would prove useful to actual people who are blind or severely visually impaired.

### 3.2.2 Data sets

The data sets were chosen so that the resulting visualizations would be something that might be typically encountered on websites e.g. as a part of a journal article. The data should be from a domain that is not too specialized and that is understandable to a wide range of people. This is why it was decided to visualize population data. Specifically it was decided to visualize the distribution of a country's population into age groups, as well as the number of births and deaths by year.

In the prototype the data was presented as belonging to the fictional country “Loremland”. The data actually is the data for Germany, but this was not disclosed in the prototype to prevent the study participants from using prior knowledge about the demographics of Germany to solve the tasks.

**Source** The data sets were all taken from the Federal Statistical Office of Germany (Statistisches Bundesamt) [Desb]. The data sets that were used are: deaths by year from 1950 to 2021 [Des23b], births by year from 1950 to 2021 [Des23a] and population by age [Desa]. All of these data sets are released under the Data licence Germany – attribution – version 2.0 [FIT].

**Preprocessing** All data sets were preprocessed before being used in the visualizations. The data set with the distribution of the population into age groups contains data for this distribution throughout the years including future predictions. Only the data from 2018 was used. In the data set there is data for each age, starting from 0 and going up to 99. Since a diagram with 100 entries might overwhelm the user, the ages were grouped into 20 groups of 5-year-ranges, starting from “0 to 4” and ending with “95 to 99”. The number of persons was then aggregated by group.

All data sets reported separate data by gender. This separation was removed by adding up the numbers of the gender-specific entries for the prototype.

### 3.2.3 Two data visualizations

It was decided to include two data visualizations in the prototype. Since research regarding the accessibility of data visualizations is still in a phase where the basics need to be better understood, two very basic visualization types, that are frequently found on the internet, were chosen for the prototype. One bar chart was included to display the

sizes of the age groups and one line chart was included to render the birth and death rate.

#### 3.2.4 Choice of technology

Since the focus of this work are data visualizations on websites, the prototype was implemented as a website with common web technologies. Even though it was implemented as a prototype, it was executed in the same way, web developers might implement data visualizations for an actual website. This was done to try out, how the recommendations could be applied in a real development setting. Since typical technologies were used, that are also frequently used in practice to create websites with data visualizations, the resulting prototype together with the results of its evaluation could then directly serve as guidance for developers who implement data visualizations in practice.

The following technologies were used to implement the prototype:

- Basic web technologies. The website was implemented using HTML, CSS and TypeScript (which compiles to JavaScript). No frontend framework (such as Vue or React) was used, since these might affect the accessibility of the result.
- d3.js for data visualization. The visualizations were implemented using the JavaScript library d3.js [Bos]. d3.js is a popular library for creating data visualizations on the web. However, accessibility studies that included data visualizations created with d3.js showed that there were issues with the accessibility of these visualizations [SCWR21]. d3.js is a rather low-level library that can be used as a flexible tool that gives a lot of freedom to the developer using it. With d3.js the developer has the responsibility for considering accessibility, as d3.js is not prescriptive and does not have any defaults in this regard. Thus, one additional goal of the creation of this prototype was, to try out, how d3.js can be used in a way, that the resulting data visualizations would be accessible.
- tone.js for data sonification. The sonification was implemented using the JavaScript library Tone.js (<https://tonejs.github.io/>). This library is made for creating music and not for creating sonifications. Thus it was a challenge to create the sonification with it. It was not possible to find a JavaScript library specifically for creating data sonifications, which is why Tone.js had to be used. Note that d3.js was also used in the sonification to create the scale that maps data values to pitch.

#### 3.2.5 Accessibility guidelines and testing

Different measures were taken to ensure the best possible level of accessibility of the prototype. The prototype was developed taking into account the Web Content Accessibility Guidelines 2.1 [W3C21] as underlying guidelines for the accessibility of the site. The visualizations in the prototype were developed following the recommendations that were synthesized from the literature in chapter 4. How the recommendations influenced the



implementation of the prototype in particular is described throughout the sections of chapter 5.

**During development** The accessibility of the prototype was continually reassessed during development. To test screen reader accessibility, Orca screen reader [Pro] with the Firefox browser on Linux was used. Additionally, the WAVE web accessibility tool [IfDRa] was used in the form of a browser extension for Firefox. To make sure that the colors that were chosen for the prototype have enough contrast, the contrast checker tool by WebAIM [IfDRb] was used. Additionally, while working on the code the linter ESLint [Fou23] was used and configured so that it would warn about possible accessibility issues that were detected by static code analysis.

**Stress test before study** Before launching the user study with the prototype, a final round of accessibility tests was done. In addition to the methods used during development, other devices, operating systems, browsers, screen readers, contrast and zoom tools were used to test the prototype. The tested operating systems included Linux, Windows, MacOS, iOS and Android. The tested browsers were Chrome, Firefox and Safari. The tested screen readers were Orca, NVDA, TalkBack and VoiceOver. Tests were also done using the operating system's built-in high contrast and zoom tools in Linux and Windows. An example for what the prototype looks like when using high contrast mode in Windows can be seen in figure 3.1.

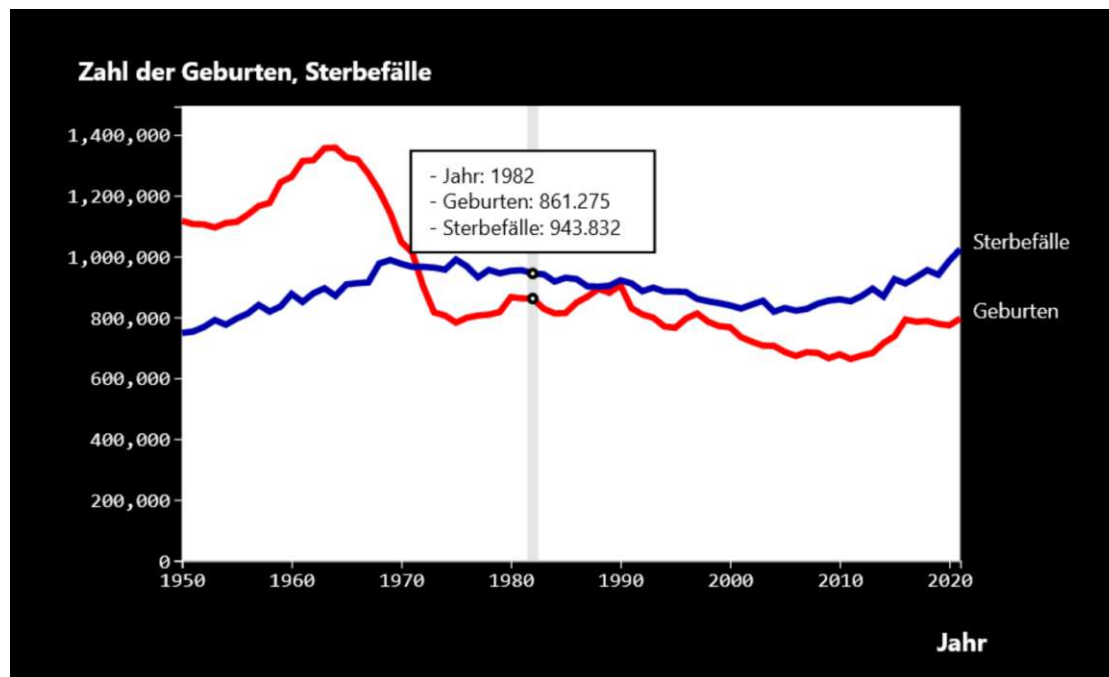


Figure 3.1: The prototype when Windows' built-in high contrast mode is active (in Firefox).

The resulting issues were fixed until the prototype was in a state where it could be tested in the user study. Some bugs remained with specific browser and screen reader combinations, but they were deemed acceptable, since the goal was to create a prototype and not a finished product.

## 3.3 Evaluation of the prototype

The prototype was evaluated in a formative and exploratory accessibility study. This was done to reach a better understanding for which techniques and features work well in order to make web-based visualizations more accessible to persons who are blind or visually impaired. The study consisted of five sessions with one blind or visually impaired participant per session. Qualitative methods were used to study how participants interacted with the prototype, whether the information in the visualizations was understandable to blind or visually impaired persons and what their thoughts on the prototype were. The results of the evaluation are described in chapter 6.

### 3.3.1 Choice of methods

The goal of the prototype evaluation study was to determine, whether the implemented accessibility features in the prototype would actually prove usable and useful when trying to understand a data visualization. Since the focus of the implemented accessibility features was on accessibility for blind and visually impaired persons, the evaluation of the prototype was done with this target group.

To see whether it is possible for this target group to extract information from the visualizations and answer typical questions related to the understanding of the data, the participants were given tasks to complete using the prototype. In this part of the study the focus was on determining, whether the accessibility features of the prototype would prove sufficient for solving the tasks, which features would be used and which kinds of tasks would prove difficult to solve with the prototype. To get a better understanding of the experiences and opinions of the target group regarding the prototype, an interview was conducted after the participant completed the task part of the study. The purpose of the interview was to understand which features they deemed valuable, which parts did not work well for them and whether anything important was missing from the prototype.

The prototype evaluation was mostly done using qualitative methods, since the goal was to develop an understanding, whether the applied techniques for accessible data visualization were useful and how they would need to be developed further in the future. The only quantitative part of the study was the measurement and evaluation of how many participants were able to solve each task correctly. This measurement was used in a supporting way to identify tasks that were difficult to solve using the given accessibility features. Time to task completion was not measured as there would have been no sensible baseline to compare the resulting times to. A comparison with other typical data visualizations would not have made sense, since these are usually not accessible, so the tasks would simply not be solvable using them.

No think aloud protocols were used during the study, since think aloud protocols interfere with screen reader use [CSFB06]. Instead, between tasks participants were asked to explain how they solved the task and asked about any interesting observations.

### 3.3.2 Setting

**Location, language and time** The study was conducted online through zoom calls. Each call was held between one participant and the researcher of the study. In total the zoom calls lasted approximately one hour each. One of the calls took two hours, since the participant was an expert in the field of the study and voluntarily offered additional feedback. The participants were located in Austria and the study was conducted in German. The study took place over the course of two days in February 2023.

**Compensation** The participants received 15-euro-vouchers for an online store as compensation for their participation in the study. One participant received a 20-euro-voucher to appreciate that they were an expert in the field and came to the study with some prepared feedback notes and took some extra time at the end of the session to present their additional feedback.

**Session recording** All participants were asked to share their screen and, if using a screen reader, the computer sound during the session. This worked for all participants except for one screen reader user, where sound sharing didn't work. As a substitute we used a feature of their screen reader where the currently selected element was highlighted with a box, this way it was visible in the shared screen, where the participant was currently at with the screen reader. The zoom sessions were recorded, including the voice of the participant and the researcher, the screen of the participant and their computer audio including the screen reader output.

**Pilot study** A pilot was conducted with one sighted person to practice and improve the protocol for conducting the study sessions.

### 3.3.3 Execution of the sessions

The sessions were divided into three parts. In the first part, the study was introduced and the participant was asked a few questions about themselves. In the second part, the participant had to complete tasks with the prototype. In the third part they were asked questions about their experience with and opinions of the prototype and its accessibility features. The following paragraphs briefly describe the different parts of the sessions. For the exact protocol that was followed during the sessions, refer to appendix A.1.

**Preparation before each session** Before the session the participants were sent an email with a consent form which explains the study and how the participants' data are collected and processed for the study. They were also already sent the link to the

prototype and asked to, if they find the time, familiarize themselves with the prototype. Four out of the five participants did this. All participants consented to participate under the conditions described in the consent form.

**Part 1: Introduction** At the start of the session the participants were introduced to the study, asked for their consent to participate and some basic data about them was recorded. This included e.g. their age, gender and previous experiences with the topic of the study. A detailed list of what data was recorded about them can be found in appendix A.2. This part of the session was not recorded, but the data given by the participants was instead entered right away into a spreadsheet. Information about the participants and their data is summarized in section 3.3.4.

**Part 2: Tasks** The participants were given seven tasks to fulfill using the prototype. All tasks were knowledge questions that could be solved using the prototype e.g. “Which age group has the highest number of people?”. The tasks were chosen to include different kinds of needed actions for solving them. The included actions were designed to loosely correspond with some of the visualization tasks defined by Brehmer and Munzner in their topology of visualization tasks [BM13].

The tasks included questions of the following types:

- Reading the value from a given location e.g. the number of births in a specific year. Corresponds to “search - locate” (locating the needed year or age group) and “query - identify” (reading the value) in [BM13].
- Finding a data point with a specific property e.g. finding the year with the highest number of births or finding the point where the lines of the line chart cross. Corresponds to “search - explore” (finding e.g. the global maximum) and “query - identify” (reading the year or age group) in [BM13].
- Describing the trend of the data in a specific part e.g. a given year range. Corresponds to “search - locate” (locating the correct part of the visualization) and “query - summarize” (understanding the trends in this area) in [BM13].

A list of the seven tasks can be found in the appendix A.3. For each task three possible answer options were prepared, but they were not offered to the participants by default, except for the questions about the trends. Participants were informed that they could ask for the three answer options any time, if they considered the task too difficult to solve without having three options to choose from. The results from this part of the study are described in section 6.1.

**Validation and iteration of tasks** To increase confidence in the results of the study, it should be avoided that difficulties encountered by the participants are due to complex data or difficult tasks. For that reason, before conducting the study with participants who are blind or visually impaired, the task part of the study was conducted with five

sighted participants. It was discovered that some tasks were too difficult and that some answer options were not ideal. The tasks were adapted after each session, until no more issues were discovered.

**Part 3: Interview** After the participant completed all tasks, a short interview was conducted. This was done while the participant still had the prototype at hand, so that the participants could show e.g. which parts were easy or difficult to use. The interview was structured and consisted of seven questions. The exact questions can be found in appendix A.4 and an English translation in appendix A.5 . The results from the interview part of the study are described in section 6.2.

### 3.3.4 Participants

The study was conducted with five participants. The participants were recruited with the help of the organization “Hilfsgemeinschaft der Blinden und Sehschwachen Österreichs” (Aid Association of the Blind and Visually Impaired of Austria). The study was planned to be done in English, but since it was not possible to find suitable participants, who were proficient enough in English, the study took place in German.

To protect the privacy of the participants, data about them will only be reported in a summarized way. Therefore the participants will not be described individually.

**Demographics** The participants were all in their forties or fifties. One participant was female and four participants were male. The participants were recruited to have varying levels of blindness or severe visual impairment. One participant stated that they were fully blind, two stated they were practically blind with some light perception, the remaining two stated that they were severely visually disabled, but not blind.

**Prior knowledge** Participants were asked whether they currently work or used to work with web accessibility. Four out of five participants stated, that they currently work or used to work with web accessibility. Out of these, two stated, that their profession involves testing the accessibility of websites, making them experts in the area of this research. One participant stated that they were not professionally involved with web accessibility.

Participants were asked whether they currently work or used to work with diagrams. Three participants replied no. One stated, that they occasionally encounter diagrams in their work. One stated, that they frequently encounter diagrams in their work.

**Devices** Participants were asked to participate with their own device and assistive technologies they are comfortable with. All participants stated, that they are confident in doing daily use activities with the device they participated with.

Three participants participated with a computer with Windows 10 or Windows 11, one participant participated with a MacBook and one participant participated with an iPhone. The participants using a MacBook and an iPhone used Safari and the built-in

screen reader VoiceOver. Out of the participants using Windows one was using Chrome, one Firefox and one Edge as their web browser. One of the Windows users used the JAWS 2023 screen reader with speech output, one used the NVDA 22.4 screen reader with speech output and a braille output device and the third did not use a screen reader, but used the magnifying glass software, that is built into windows.

#### 3.3.5 Evaluation of the recorded data

Each session was recorded including the sound and the shared screen. These recordings were evaluated together with the data about the level of vision and the used technology of the participants.

**Transcription of the recordings** For the evaluation the recordings were transcribed. During the task part, it was transcribed what the participants were doing, what difficulties they encountered, whether they correctly solved the tasks and whether they asked to be given the answer options. When they made any remarks regarding e.g. features they liked or features that did not behave as expected, this was transcribed verbatim. The interview part and any discussions relating to the accessibility of the visualizations were also transcribed verbatim. Any comments that were not related to the accessibility of the visualizations were not included in the transcript.

**Evaluation of the task part** To evaluate the task part the transcripts of the sessions were used. For each task the relevant parts of the transcripts of all participants, meaning the part where the participant worked on this task, were copied together into one document. One section was created for each task. Within each section, subsections were created that contained the transcript excerpt from when that participant worked on that task.

It was then counted from the transcript excerpts, how many of the participants correctly solved this particular task and how many participants asked to be given the answer options. Afterwards it was analyzed from the transcripts, how the successful participants had used the visualizations to solve the task. The transcripts were also examined to identify the issues that were encountered when the participants worked on the task. The results were then summarized and described. This was done for each of the seven tasks. The result of this evaluation can be found in section [6.1](#).

**Evaluation of the interview part** For the evaluation of the interview questions the transcripts were used, too. For each interview question the answers of all participants to that question were copied together into one document. The document had one section for each question and within each section a subsection for each participant.

After copying together the direct answers to this question, each transcript was once more read completely and examined to identify parts where the participant said something that was also relevant to the interview questions. These snippets were then also added to the participants subsection of that question. For instance, if a participant mentioned,

while working on a task, that the table is very useful to them, this was added to the snippets of that participant relating to the question about liked and useful features. For each interview question the answers and the other relevant snippets were then analyzed, summarized and described. The result of the evaluation is described in section 6.2.

**Evaluation of further results** Some interesting observations and statements fit neither into the evaluation of the tasks, nor into the evaluation of the interview questions. Since these occurrences were too valuable to ignore, one additional round of evaluation of the transcripts was done to capture them. In this round each transcript was analyzed to identify parts that had not yet been included in the task or the interview evaluation. This included e.g. observations where a participant overlooked a feature of the prototype. All of these observations and statements were copied together into one document and then described. The result of this process can be found in section 6.3.



Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar  
The approved original version of this thesis is available in print at TU Wien Bibliothek.



# Synthesized recommendations

Researchers have started to make recommendations on how to make data visualizations more accessible for people who are blind or visually impaired. This chapter presents the recommendations synthesized from other works. The process, that was used to arrive at these recommendations, is described in section 3.1. The works that were identified to include relevant recommendations and that were subsequently used in the synthesis of the recommendations are listed in table 4.1.

## 4.1 Synthesized recommendations

The following recommendations were synthesized according to the process described in section 3.1.

### 4.1.1 Standards and best practices

Follow existing standards and best practices. This includes:

- Considering accessibility throughout the entire design and development process [Str21b].
- Following known standards for the creation of accessible websites, such as the W3C's Web Content Accessibility Guidelines [W3C21][Ela22, Str21b].
- Writing semantically correct HTML, e.g. using `<button>` to create a button [Ela22].
- Supporting a variety of devices and browsers [Ela22].
- Using known tools and user testing to help ensure the result is accessible [Str21b, Ela22].

Title	Authors	Year
“ASVG - Accessible Scalable Vector Graphics: intention trees to make charts more accessible and usable” [WOH <sup>+</sup> 15]	M. Weninger, G. Ortner, T. Hahn, O. Drümmer, and K. Miesenberger	2015
“Methodology for heuristic evaluation of the accessibility of statistical charts for people with low vision and color vision deficiency” [AMTGS21]	R. Alcaraz Martínez, M. Ribera Turró, and T. Granollers Saltiveri	2021
“Accessible Visualization: Design Space, Opportunities, and Challenges” [KJRK21]	N. W. Kim, S. C. Joyner, A. Riegelhuth, and Y. Kim	2021
“COVID-19 highlights the issues facing blind and visually impaired people in accessing data on the web” [SFK <sup>+</sup> 21]	A. F. Siu, D. Fan, G. S.-H. Kim, H. V. Rao, X. Vazquez, S. O’Modhrain, and S. Follmer	2021
“Understanding Screen-Reader User’s Experiences with Online Data Visualizations” [SCWR21]	A. Sharif, S. Shivani Chintalapati, J. O. Wobbrock, and K. Reinecke	2021
“Beyond “Alt-Text” Creating Accessible Data Visualizations with Code” [Str21a]	Adam Strantz	2021
“Using Web Standards to Design Accessible Data Visualizations in Professional Communication” [Str21b]	Adam Strantz	2021
“The Chartability Workbook” [Ela22]	Frank Elavsky	2021 (ongoing)

Table 4.1: The works that have been included in the synthesis of the recommendations.

### 4.1.2 Screen reader discoverability

Make sure screen reader users understand when they encounter data visualization e.g. by providing a label with the text “chart” that will be read out when the data visualization receives focus [KJRK21, SCWR21].

### 4.1.3 Colors and contrast

Text and graphic elements need to have sufficient contrast with their background [AMTGS21, Str21b, Ela22]. Text should have a contrast ratio of at least 4.5:1 and graphic elements of at least 3:1 [AMTGS21, Ela22]. When color is used to show that an element changed its state, the new state needs to have a contrast ratio of at least 3:1 in comparison to the previous state [Ela22]. Focus indicators need to have a contrast ratio of at least 4.5:1 in comparison to the background [Ela22].

Color schemes need to be designed so that persons with color vision deficiencies can differentiate the included colors [AMTGS21, Ela22] and color alone should not be used to communicate information [Ela22]. For instance, patterns, shapes and size variations can be used as a second channel to communicate the information [Ela22].

### 4.1.4 White space

The visualization should use an appropriate amount of white space between elements so that the elements are understandable and distinguishable [Ela22, Str21b]. Make sure elements are not unnecessarily overlapping each other [AMTGS21, Ela22] and generally do not include too many elements in the visualization [Str21b]. Unless required by the type of visualization, adjacent elements such as bars in a bar chart should have at least one pixel of white space between them [Ela22]. If the data the visualization is built from can change, the visualization needs to be able to handle outliers and other extreme cases in the data gracefully without becoming incomprehensible [Ela22].

### 4.1.5 Text

Any text in the data visualization needs to be legible [AMTGS21, Str21b, Ela22]. The size of the text should be at least 9pt or 12px, preferably larger [Ela22]. Use a legible font family, pay attention to the spacing of letters, words and lines, and make sure hard to read styles such as italics and capitalized text are only used sparingly [AMTGS21]. Numbers need to be rendered in a format that is easily readable e.g. through appropriate use of units and punctuation [Ela22]. The numbers also need to be formatted appropriately for screen readers, so that they will be read correctly [Ela22].

### 4.1.6 General orientation

Make sure to include elements that help accessible orientation when interacting with the data visualization [KJRK21]. This includes:

- Adding an accessible title or caption to the visualization [AMTGS21, Ela22].
- Clearly and accessibly labeling all elements and placing the labels close to the elements they belong to [Ela22].
- Including accessible axes and labeling them clearly with a title [Ela22, AMTGS21]. If applicable, the axis labels need to include the unit of the data [AMTGS21]. Grid lines can be added as long as they are not adding too much visual noise to the visualization [AMTGS21].
- Adding an accessible legend that explains all marks used in the visualization e.g. patterns and colors [AMTGS21]. If possible, legends should be placed on the top-left part of the visualization, so that they can be discovered early when using a screen reader [KJRK21].
- Accessibly stating the source and date of the used data and a link to the original source [AMTGS21].
- Offering a non-visual way for getting an overview of the data e.g. through providing descriptive statistics or sonification [KJRK21].

### 4.1.7 Descriptions for screen reader users

Allow screen reader users to access both, an overview of the visualization and a way to access more detailed information [SCWR21, KJRK21]. One way to offer an overview is by providing a short textual description that will be read out by the screen reader [SCWR21]. Listening to a brief description of the visualization will allow screen reader users to decide, whether they want to further interact with it [KJRK21, AMTGS21]. This brief description could, for instance, include a statement of the main takeaways, structure of the visualization and descriptive statistics [KJRK21].

Screen reader users need to be provided with a way to access the details of the visualization [SCWR21]. There are different ways for achieving this. One of the options would be to provide a textual long description of the visualization [KJRK21]. Structured markup such as HTML can be used to make the long description easier to navigate, so that screen reader users don't get overwhelmed by the large amount of text [KJRK21]. The long description could be divided into three parts: first, an overview, that states what the visualization is about and some key features, second, the values e.g. in the form of a navigable data table, and third, the presentation, which explains in detail which parts the visualization consists of and how to read it [Str21b].

To make sure any textual descriptions are up-to-date and accurate, they can ideally be dynamically generated directly from the data the visualization is based on [SCWR21].

Any visible features of the data such as clusters, outliers and trends need to be described in text, so that they are also available to screen reader users [Ela22].

### 4.1.8 Drilling down with a screen reader

Data visualizations need to offer screen reader users a way to drill down and explore the details of the data [SCWR21]. The individual elements of the data visualization

need to be interactively navigable using assistive technology [WOH<sup>+</sup>15]. This includes making the individual data points accessible in some way [SCWR21]. The data points might e.g. be made accessible through a data table [SCWR21] or by allowing users to play a sonification point by point [KJRK21]. Generally, the navigation should follow the logical order and hierarchy of the visualization and its data [Ela22]. While navigating through individual data points, the user would ideally be provided with an option to receive additional information on each data point on request, for instance, information on where the user is right now and how the value of the current data point relates to the surrounding values [KJRK21]. If possible, HTML markup can also be used to facilitate fast direct access and the possibility to better compare data points by allowing screen reader users to jump between data points and different parts of the visualization e.g. through the use of links [SFK<sup>+</sup>21]. Generally, the visualization should not be provided as a static image, but using markup, so that individual elements can be made accessible more easily [Str21a].

#### 4.1.9 Usable keyboard navigation

Any interactive elements of the visualization need to be reachable and focusable using a keyboard [Ela22]. Elements that are not interactive should not have a tab stop when navigating with the keyboard [Ela22]. The currently focused element needs to be highlighted, so that the user knows which element they are on [AMTGS21, Ela22]. The focus indicator should have a border of at least 2px and a contrast of at least 4.5:1 in comparison to its background [Ela22]. In addition, the currently focused element might be magnified [WOH<sup>+</sup>15]. The focus order needs to be logical and follow the structure of the visualization [Ela22]. If large blocks of repetitive content are present, there needs to be a way to skip them [Ela22].

#### 4.1.10 Interactivity

If the visualization includes interactive parts, users need to be informed of how to use them [Ela22]. The user also needs to be informed of any custom keyboard shortcuts and these keyboard shortcuts must not interfere with regular navigation on the page or with shortcuts of assistive technology such as screen readers [Ela22]. If actions use custom controls that make them difficult to perform (e.g. for brushing), there needs to be a simple alternative for performing the same action that is accessible regardless of the input device used [Ela22].

If parts of the page or the visualization change e.g. as a result of an action, screen reader users need to be informed of these changes [Ela22]. If data points change their location in the visualization, animations should be used so that users can better follow the change [Ela22].

### 4.1.11 Customization

The visualization needs to respect any custom style rules the user applied using assistive technology e.g. style sheets that enlarge the font or change the color theme of websites [AMTGS21, Ela22]. The visualization could also offer its own system for customizing the presentation [AMTGS21]. There should be an option for the user to adapt contrast and, if applicable, chart textures [Ela22]. If non-standard scrolling behavior such as infinite scroll or non-linear scrolling is used in the visualization, there needs to be a way to change or disable this [Ela22].

### 4.1.12 Multiple ways and multimodality

Allow users to explore the data using different ways and modalities e.g. in addition to the visualization, provide sonification, data tables and data downloads [SCWR21]. Multiple modalities can also be leveraged at the same time while the user interacts with the visualization [KJRK21]. Providing multiple ways to explore the data allows users to find a way to interact with the data that works well for them personally [SFK+21]. Furthermore, this allows for the weaknesses of some representations and modalities to be compensated by other representations [SFK+21]. The time needed to explore the visualization should be appropriate regardless of which way the user chooses for interacting with the visualization [Ela22]. If the visualization is interactive, there should be more than one way to reach specific drilled-down states and actions that are complex to perform (e.g. for brushing and filtering) should have simple alternatives to achieve the same result [Ela22].

### 4.1.13 Data table

Provide a table that displays the data that is represented in the visualization [AMTGS21, Ela22]. An exception can be made if other features of the visualization already accessibly provide the same information that would be provided through the table [Ela22]. Ideally, data tables should be sortable, filterable and downloadable [Ela22]. Data tables are one way to allow screen reader users to drill down if they are interested in details [SCWR21]. Data tables can also help increase confidence in the data as it enables users to verify the information they receive from the visualization [SFK+21].

### 4.1.14 Data download

Provide an option for downloading the data that was used to create the visualization [Ela22, SFK+21, SCWR21]. This way users can use their own tools and methods to understand the data instead of relying on the provided representation [SFK+21].

### 4.1.15 Zoom

The data visualization needs to support zooming using the browser's built-in zoom function [AMTGS21, Ela22] as well as zooming through assistive technology [Ela22]. The

visualization needs to adapt the size and layout of its elements, as well as font sizes, so that the visualization is still legible, understandable and usable when the user zooms [AMTGS21, Ela22]. Zooming should not result in the user needing to use horizontal and vertical scrolling at the same time in order to use the visualization [Ela22].

#### 4.1.16 Device-independent access

The data visualization needs to be accessible using a variety of different devices e.g. mouse, keyboard, screen reader or touchscreen [Ela22]. Any visual content needs to also be accessible via screen reader [Ela22]. Any interactive parts of the visualization need to be usable independently of the input device the user is using to access the visualization [AMTGS21, Ela22] e.g. a hover interaction needs to also be accessible through focusing the element using the keyboard [Ela22].

#### 4.1.17 Consistency

If multiple visualizations are present on one page or on different pages, their design and interaction patterns should be consistent with each other [Ela22]. Furthermore, if the user changes any settings in the visualization, these should be applied to the other visualizations, too [Ela22].

#### 4.1.18 Appropriateness

Consider the user's goal or task when choosing the (accessible) representations to provide, so that the representations will be useful for the task at hand [SFK<sup>+</sup>21].

#### 4.1.19 Explanations

When providing definitions of abbreviations or specific terms, make sure you add the definition directly next to that term [SFK<sup>+</sup>21] or link from the term to its definition [AMTGS21]. In HTML the `<abbr>` can be used for abbreviations [AMTGS21].

## 4.2 Summary

This chapter presented 19 recommendations for creating web-based visualizations that are accessible to people who are blind or visually impaired. The recommendations were synthesized from findings and suggestions provided by other works. The next chapter presents a prototype that was developed based on these recommendations.



Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar  
The approved original version of this thesis is available in print at TU Wien Bibliothek.



# The prototype

To test the synthesized recommendations in practice, a prototype in the form of a website with data visualizations was created. The website includes two data visualizations that model one way of translating the recommendations into practice. This chapter describes the visualizations, their accessibility, and how the recommendations from the previous chapter influenced the design of the prototype.

The full source code of the prototype and a link to the prototype website have been published on GitHub<sup>1</sup> and can be publicly accessed there. For information about the development process and technology choices, please refer to chapter 3.

## 5.1 Overview

The prototype website contains two main pages, one for each visualization. In total, there are seven pages:

1. The start page: The page from which users can then navigate to the bar chart (referred to as prototype one) or the line chart (referred to as prototype two). Screenshot in figure 5.1.
2. The main bar chart page: The main page of the bar chart, which includes the visualization along with the accessibility features (e.g. the sonification) and links to the fullscreen version and the table version of the chart. Screenshot in appendix A.6.
3. The fullscreen view of the bar chart: A page on which only the visualization is included and can be zoomed using button controls.
4. The table view of the bar chart: A page on which the underlying data of the visualization is displayed in a table.

---

<sup>1</sup><https://github.com/Anne-Victoria/Accessible-Data-Viz-Prototype>

5. The main line chart page: The main page of the line chart, which includes the visualization along with the accessibility features (e.g. the sonification) and links to the fullscreen version and the table version of the chart. Screenshot in figure 5.2.
6. The fullscreen view of the line chart: A page on which only the visualization is included and can be zoomed using button controls.
7. The table view of the line chart: A page on which the underlying data of the visualization is displayed in a table.

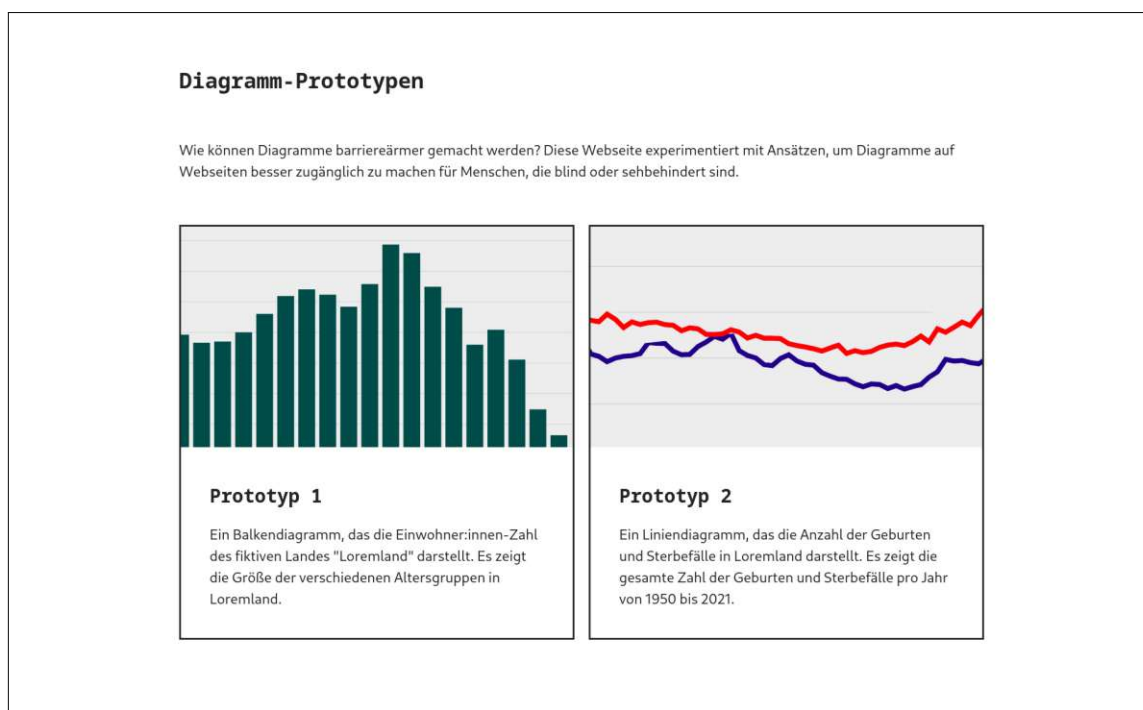


Figure 5.1: The start page of the prototype which links to the visualization pages

### 5.1.1 The main visualization pages

The main visualization pages as well as the subordinate pages for the fullscreen view and the table view were designed to be mostly identical to each other in their design and behavior. This was done to honor recommendation 4.1.17, which states that the design and interaction patterns between visualizations on one website should be consistent. For this reason, while discussing the general structure of the page, it suffices to describe one of the two main visualization pages. The details of the visualizations, which differ, as they are different types of visualizations, will be presented in sections 5.2 and 5.3.

An example of one of the main visualization pages can be seen in figure 5.2, which shows a screenshot of the main line chart page. The main visualization pages consist of the following elements:

1. A link back to the start page.
2. A main heading “Prototype 2 - Number of births and deaths per year in the fictional country Loremland from 1950 to 2021”.
3. An instructional text that explains how to use the visualization. Described in section 5.4.4.
4. The chart itself. Described in sections 5.2 (bar chart) and 5.3 (line chart).
5. A button for opening the fullscreen view. Fullscreen view is described in 5.4.10.
6. A section “Sonification” that allows the user to listen to the data. Described in section 5.4.13.
7. A section “Download” that allows the user to download the data. Described in section 5.4.12.
8. A section “Table” that links to a separate page on which the data is displayed in a table. Described in section 5.4.11.

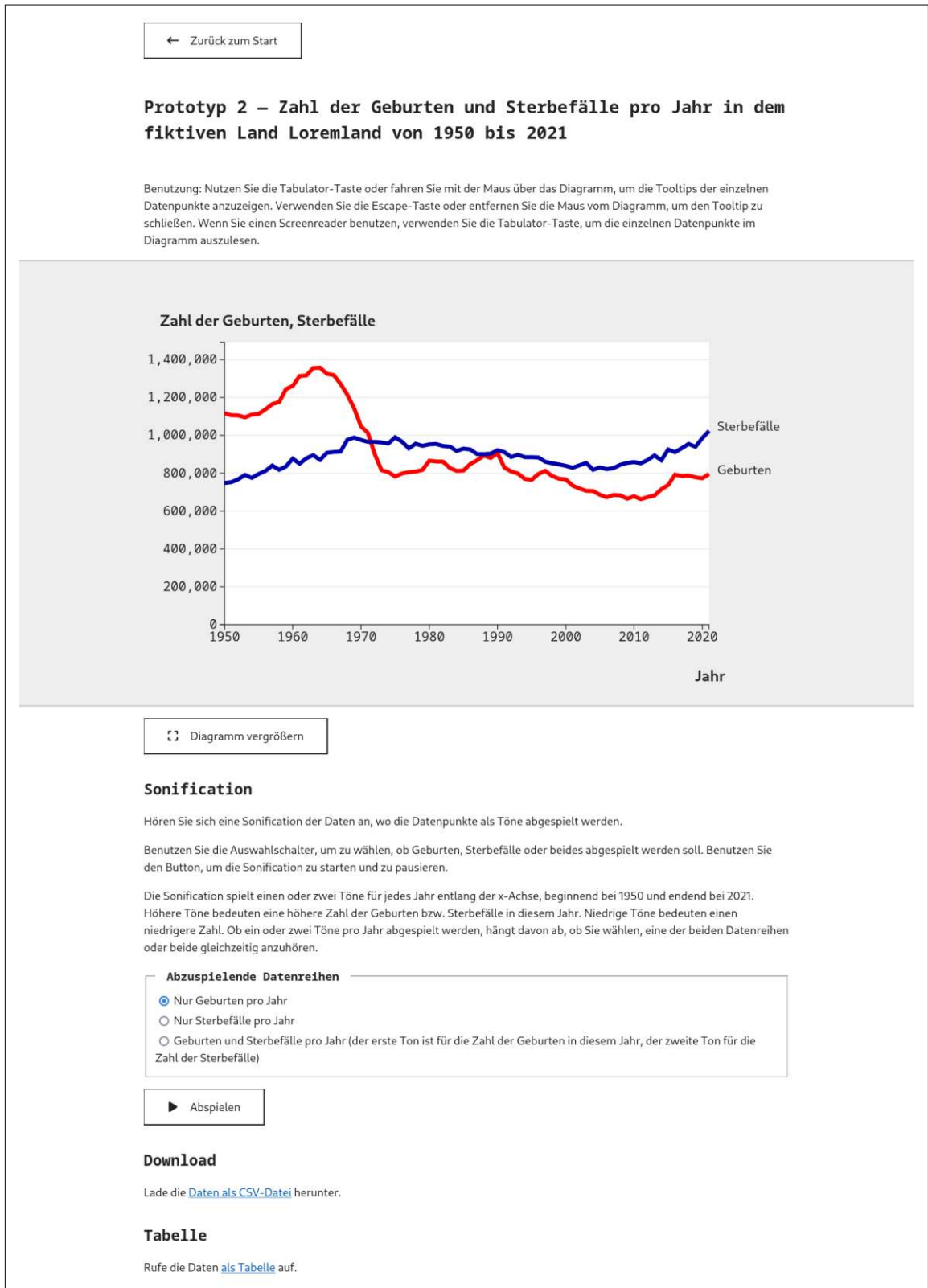


Figure 5.2: The main page of the line chart visualization

## 5.2 The bar chart

The first data visualization in the prototype is a bar chart. It visualizes the distribution of the population of the fictional country “*Loireland*” into age groups. Within the prototype website this visualization is referred to as prototype one. For a screenshot of the visualization, see figure 5.3. The x-axis shows the different age groups from “0 - 4” to “95 - 99”. Population aged 100 and older is not included in the visualization. The y-axis shows the absolute number of persons in this age group. The size of each age group is represented by a dark green bar. Since the data is a distribution, a histogram without gaps between the bars might have been a more common choice than a bar chart. However, one results of the synthesized recommendations was, that there should be gaps between bars to make them easier to distinguish (see recommendation 4.1.4). Therefore gaps of white space were included between the bars.

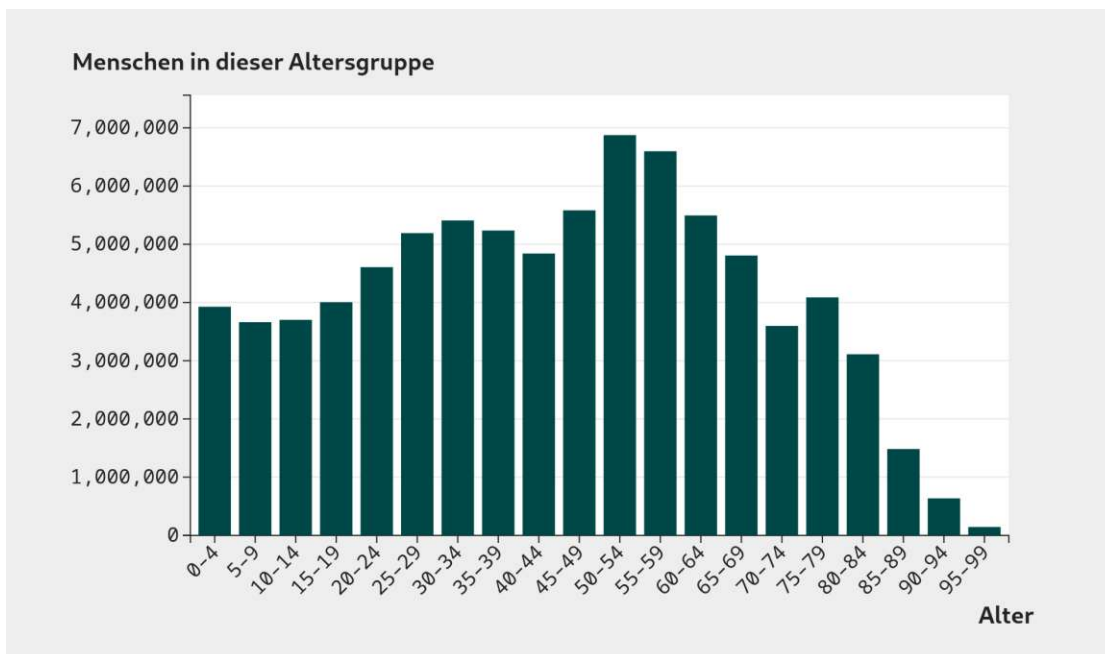


Figure 5.3: The bar chart visualizing the distribution of the population into age groups

## 5.3 The line chart

The second data visualization included in the prototype is a line chart that displays the number of births and deaths in the fictional country “*Loireland*” over time. Within the prototype website this visualization is referred to as prototype two. A screenshot of the visualization can be seen in figure 5.4. The x-axis shows the years from 1950 to 2021. The y-axis shows the absolute number of births and the absolute number of deaths in that year. The number of deaths and number of births throughout time are encoded by

lines that show how the values change over the years. The lines were colored red (for births) and blue (for deaths) to make them easier to distinguish at intersecting points. The identity of each line is given by a label at the end of the line, that states “deaths” and “births” respectively.

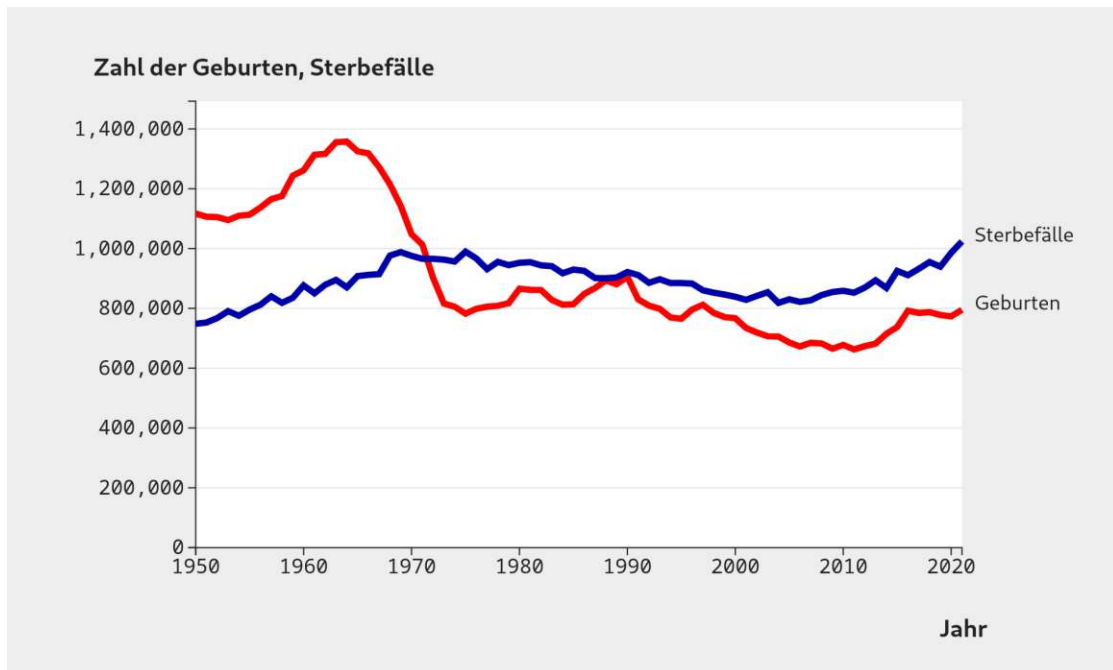


Figure 5.4: The line chart visualizing the number of births and deaths per year.

## 5.4 Accessibility features

In order to make the visualizations in the prototype as accessible as possible, many different ways to access the information in the visualization were included. This is in line with recommendation 4.1.12 which suggests that users should be allowed to explore the data in multiple ways e.g. via a table in addition to the visualization itself. This section describes all accessibility features that were included in the visualization. This includes the different ways of making the data available, such as through sonification and data tables, but also includes general accessibility features and considerations such as choosing appropriate colors and making the pages responsive.

### 5.4.1 Colors

The colors in the visualizations were chosen such that they would have a high contrast and would be easy to distinguish including for people with color vision deficiencies.

**Base colors** Generally, recommendation 4.1.3 was followed in this regard. To achieve a high contrast ratio and to make colorful and black elements stand out, white or near-white was chosen for backgrounds throughout the page and visualizations. Black or near-black was chosen for texts and basic visualization elements such as the axis lines.

**Bar chart** In the bar chart, no data dimension is mapped to color. But still the bars of the chart are colored, though all in the same dark green color (#004747). This color was chosen to have a high contrast with the white background.

**Line chart** In the line chart the two data series are represented by lines of different colors. There are two lines, one is blue and the other is red. The red (#ff0000) and blue (#0000aa) colors were chosen specifically so that they would have a high contrast with each other and with the white background and so that people with color vision deficiencies would be able to distinguish them without problems. A color picker tool by David Nicols [Nic] was used to choose the colors and to test that they would be distinguishable to people with various color vision deficiencies. Figure 5.5 shows the chosen colors and a simulation of how they might appear to people with color vision deficiencies.

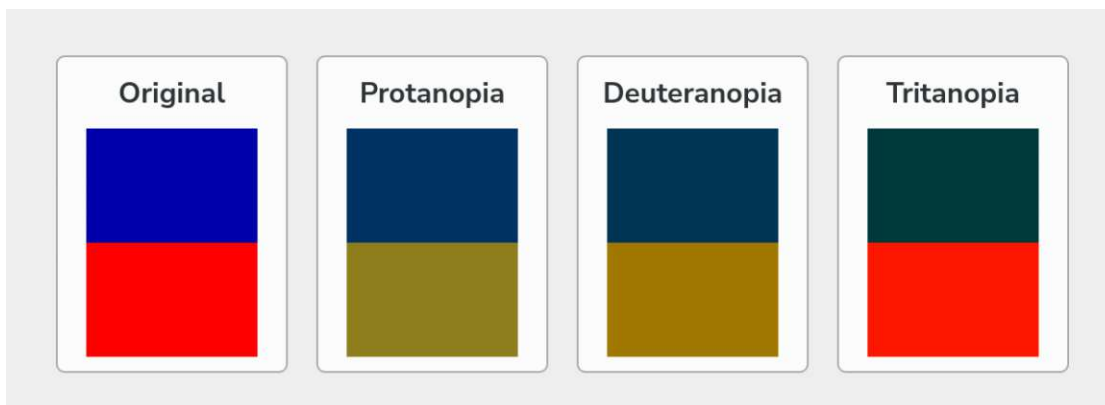


Figure 5.5: The colors chosen for the line chart in a color vision deficiency simulator [Nic]

**Focus indicator** The focus indicator that indicates which element is currently focused when navigating with the keyboard was given a blue color (#005fbd) that sufficiently stands out from the white background.

**Custom colors** In accordance with recommendation 4.1.11 custom user style sheets and high contrast modes should be respected by the visualization. It was tried to honor this as much as possible, so that the result would be readable when high contrast modes were used by the user. An example can be seen in section 3.2.4 figure 3.1.

### 5.4.2 Text

As per recommendation 4.1.5 the text was styled to be as legible as possible. To achieve this, different measures were taken.

**Font sizes** In the text of the website no base font size was set, so that the page would use the font size the by the user in the browser settings. This is usually 16px by default, which is accepted as a generally legible size. Within the elements of the visualization itself, the font had to be forced to 16px, since otherwise text might get too large and break out of its container, such as the tooltip box.

**Font families** For good legibility a system font stack was chosen. This means, that via CSS the page was configured so that a font that is usually used on the device of the user already will be picked to display the page. The code for this can be seen in listing 1.

```
body {  
  font-family: system-ui, 'Segoe UI', Roboto, Oxygen-Sans,  
    Ubuntu, Cantarell, 'Helvetica Neue', sans-serif;  
}
```

Listing 1: The CSS code for a system font stack which allows the browser to pick a font that is already commonly used on the user's device.

**Number formatting** Numbers were formatted in a way that they would be legible when reading them, as well as when read by a screen reader. For this purpose they were rendered with a monospaced font and right-aligned in the table and the axis labels. In the tooltips this was not done. For better readability by the eye and by screen readers a dot was used as thousands separator throughout the prototype. However, one mistake was made in the axis labels, where accidentally commas were used as thousands separators. This is incorrect, since in a German locale, the dot needs to be used to separate thousands. However, in all other parts of the prototype it was done correctly and screen reader users were not affected, since the axis labels were replaced for screen readers by an axis description that used the correct thousands separator.

### 5.4.3 Responsiveness

To allow users to freely zoom and view the prototype on different devices such as a laptop or a phone, the website was implemented using responsive design. All elements of the website adapt themselves to the current size of the screen. The visualization gets larger and smaller when resizing the screen, too. When the screen gets so small, that the visualization would get unreadable if it was shrunk to fit the screen width, the visualization stops shrinking and instead a horizontal scroll bar appears within the visualization that allows the user to view the visualization through scrolling left and



right without compromising the legibility of the text. The responsiveness was generally implemented in accordance with recommendation 4.1.15, however, it was not possible to avoid requiring the user to use horizontal and vertical scrolling on small screen sizes.

#### 5.4.4 Usage instructions

As per recommendation 4.1.10 any interactive elements of a visualization need an explanation as to how they can be used. To follow this recommendation, the usage of the interactive parts of the visualization was explained on the page. Firstly, an explanation for opening and closing the tooltips using different input devices was included. It was also stated that the individual data points in the visualization can be accessed with a screen reader using the `tab` key or the arrow keys. Further down at the sonification feature, an explanation was included about how the sonification works and how the user can choose what data to listen to (in the case of the line chart) and how they can start and stop the sonification.

#### 5.4.5 Tooltips

When hovering a bar in the bar chart or any time slice in the line chart, a tooltip appears that displays the details of that year or age group. An example can be seen in figure 5.6.

As required by 4.1.16 and 4.1.9 the tooltips are usable using different devices including a mouse, keyboard, screen reader or touch screen. As per recommendation 4.1.10 the usage of the tooltips is explained in a text above the visualization.

Once a tooltip appears, it stays visible while the user still hovers the bar in the bar chart or the time slice in the line chart. But the user can also move the mouse over the tooltip itself and it will stay open. This was done in compliance with WCAG 2.1 [W3C21] and is important e.g. for people using screen magnifiers. The tooltip can be dismissed by moving the cursor away or by pressing the `escape` key on the keyboard, as suggested by WCAG 2.1 [W3C21].

In the line chart a light gray vertical line and two dots were included to help orientation with the tooltips. The gray line highlights the currently selected time slice i.e. year for which the tooltip is displayed. The dots show directly on the two lines where the data points are for which the tooltip displays the values. Since the dots have excellent contrast, the additional vertical line was kept light with a low contrast as to not visually clutter the chart unnecessarily. In the bar chart indicators like this were not necessary, since the bars were wide enough to tell apart and since the tooltip could be easily directly connected to the currently selected bar by a short black line.

One more difference between the tooltips of the bar chart and the line chart is, that the text inside the tooltips of the line chart starts with a dash in each row. This was done, since it could otherwise become confusing which value belongs to which data series when the tooltip content is read out by a screen reader.

As the implementation of the tooltips was not very straightforward, it can not be described here in detail. In case of interest in the implementation details, please refer to

the source code on GitHub<sup>2</sup>.

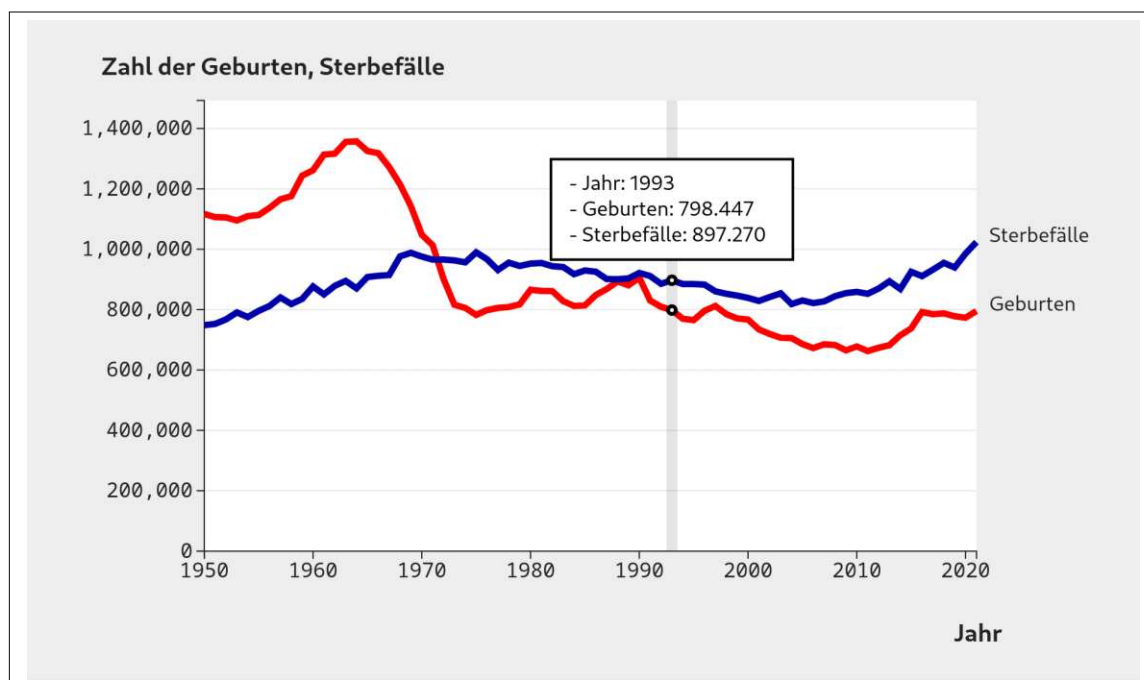


Figure 5.6: The line chart with a tooltip that reads out “Year: 1993”, “Births: 798.447”, “Deaths: 897.270”.

#### 5.4.6 Labels at end of line

In the line chart the lines were not identified by a legend, but were labeled directly at the end of the line by a text label. This can be seen in figure 5.4. This was done since recommendation 4.1.6 suggests that labels should ideally be placed closely to the element they are labeling. The idea is that this helps e.g. users, who use a strongly magnified view, to quickly find the labels. An added benefit is, that this way, color is not used to make an association between line and its identifier, as would be the case with a traditional legend. This way there is no danger of people with a color vision deficiency associating the lines and the labels wrongly.

#### 5.4.7 Overview and trend descriptions

Recommendation 4.1.6 states that there needs to be a non-visual way of getting an overview of the data presented in the visualization, for instance by including a textual description. Recommendation 4.1.7 more specifically requires a description of the visualization for screen reader users that offers an overview and a description of the

<sup>2</sup><https://github.com/Anne-Victoria/Accessible-Data-Viz-Prototype>

visual features such as trends. To follow this recommendation two description texts were included in each visualization. One overview description and one trend description. They were included at the start of the visualization, but visually hidden, so that they are only accessible using a screen reader. This was achieved by giving the elements a CSS class and then using CSS rules to hide the elements with this class. The CSS code can be seen in listing 2.

Note that, as included in recommendation 4.1.7, previous works such as Sharif et al [SCWR21] have suggested, that textual descriptions could ideally be automatically generated from the underlying data. But because of the constraints of developing a prototype the textual descriptions were not generated, but written by hand in this case.

```
.screen-reader-only {
  clip: rect(0 0 0 0);
  clip-path: inset(50%);
  height: 1px;
  overflow: hidden;
  position: absolute;
  white-space: nowrap;
  width: 1px;
}
```

Listing 2: The CSS code for hiding an element visually, but keeping it accessible for screen readers. Implemented as suggested by Coyier in [Coy19].

The overview description explains what is depicted in the visualization, which elements it consists of and what the minimum, maximum and average of the values are. As the prototype is in German, the descriptions are in German, too. Below is a translated version of the overview description included in the prototype.

*“Graphic. Diagram. Overview: A line chart showing the number of births and deaths per year in Loremland. The x-axis shows the year from left to right from 1950 to 2021. The y-axis shows the absolute number of births and of deaths in that year from 0 to 1,400,000. There are two lines. One line represents the number of births per year. The maximum is at 1,357,304 births in 1964. The minimum is at 662,685 births in 2011. The average is 906,972 births per year. The other line represents deaths per year. The maximum is at 1,023,687 deaths in 2021. The minimum is at 748,329 deaths in 1950. The average is 890,155 deaths per year.”*

The trend description describes the trends that are visible in the visualization. Since the question of what trends are visible in a visualization and how they are most accurately described can be subjective, the trend descriptions were written together with one other sighted person until descriptions were reached that both persons deemed sufficiently accurate. An example for one of the trend descriptions is given below, in the form of an English translation.

*“Trends: The number of births gradually increases, then abruptly drops until 1973. Afterwards it slightly fluctuates on a lower level. The number of deaths slightly increases at first, then slightly decreases, then slightly increases again. The number of deaths starts out much lower than the number of births, but first surpasses it in 1972 during the steep drop of births. After that it stays above the number of births until the end.”*

#### 5.4.8 Discoverability

According to recommendation 4.1.2 it needs to be understandable to screen reader users when they encounter a visualization. To communicate this, the `div` that encloses the elements of the visualization was given a `role` and `aria-label` that communicate to screen reader users that they are now on a visualization. This can be seen in listing 3. Depending on which screen reader is used, something like “Grafik. Diagramm.” (English “Graphic. Diagram.”) will be read out, when the user encounters the visualization. Note, that since some screen readers do not read this text out properly, it was also added to the start of the textual overview description of the diagram.

```
<div
  id="births-deaths-viz"
  class="viz-container"
  role="figure"
  aria-label="Diagramm"
>
  <!-- The elements of the visualization are placed here. -->
</div>
```

Listing 3: The wrapping `div` of the visualizations with the “`role`” and “`aria-label`” attributes that improve discoverability for screen reader users. “Diagramm” is German for “diagram”.

#### 5.4.9 Accessing the elements of the visualization with a screen reader

The data visualizations were implemented so that the individual elements of the visualizations would also be accessible to screen reader users. This includes accessibility of the bars in the bar chart and dots on the lines of the line chart, but also the accessibility of the axes and labels. This was made possible since the visualization was created using `d3.js` [Bos] and all elements of the visualization are dynamically generated SVG (Scalable Vector Graphics) elements that are part of the website’s DOM (Document Object Model). Even though SVG elements are not the same as HTML elements, their accessibility can in some ways be similarly influenced as with HTML elements. For instance, the attribute `aria-hidden` for hiding an element from screen reader users works for HTML as well as SVG elements. Accessibility of the individual elements of the data visualizations was implemented, since this was suggested by recommendation 4.1.8.

**Accessibility of the axes** To make the axes of the visualizations screen reader accessible, the first step was to hide the individual tick marks e.g. “200.000”, “400.000” and so on, as they are, without context, not very useful for screen reader users. This was done by using `aria-hidden="true"` on the grouping element that wraps the tick marks. Then a description of the axis was invisibly added in the same place to provide a screen reader accessible alternative. An example for this implementation, including an example for the text description of an axis can be seen in listing 4. The code for hiding the axis description visually can be seen in listing 2.

```
// Render x-axis
svg
  .append('g')
  // Hide the individual tick marks from screen readers
  .attr('aria-hidden', 'true')
  .attr(
    'transform',
    `translate(0, ${heightWithoutMargins})`
  )
  .call(d3.axisBottom(xScale))
  .selectAll('text')
  .attr('transform', 'translate(-10,0) rotate(-45)')
  .style('text-anchor', 'end');

// Render x-axis screen reader text
svg
  .append('text')
  .attr('fill', '#00000000')
  .attr('class', 'screen-reader-only')
  .text(
    'X-Achse, zeigt Alter, aufgeteilt in zwanzig
    Altersgruppen beginnend mit 0-4 und endend
    mit 95-99.'
  );
```

Listing 4: The screen reader accessible implementation of a chart axis. Translation of the axis description text: “X-axis, shows age, split into twenty age groups starting with 0–4 and ending with 95–99.”

**Making the data points accessible** When tabbing through the data visualization using the keyboard (or a screen reader), the user actually navigates through the SVG elements that represent the data points in the data visualization. The `tabindex="0"` attribute has been used to allow the data points to receive focus when navigating through the page using a screen reader or a keyboard. Furthermore, each data point element is

linked to its tooltip via an `id`. The tooltip already contains a textual representation of the data point. So this is then used to achieve a satisfactory screen reader output when the user navigates through the data points. Each data point is associated with the content of its tooltip using the `aria-labelledby` attribute. So when the user focuses a data point, the content of the tooltip will be read out. An example for this implementation can be seen in listing 5.

```
// Render the bars
const bars = svg.selectAll('mybar').data(data);
const rectangles = bars
  .join('rect')
  .attr('x', (d) => `${xScale(d.age_group)}`)
  .attr('y', (d) => yScale(d.population_size) ?? 0)
  .attr('width', xScale.bandwidth())
  .attr(
    'height',
    (d) =>
      heightWithoutMargins -
      (yScale(d.population_size) ?? 0)
  )
  .attr('fill', '#004747')
  /* Make the data point focusable */
  .attr('tabindex', '0')
  /* Each bar is labeled by its tooltip */
  .attr('aria-labelledby', (d) => `tooltip-${d.id}`);
```

Listing 5: The screen reader accessible implementation of the bars in the bar chart.

**Focus order** When using either the keyboard to tab through web content or a screen reader to navigate through it sequentially, the elements of the website usually receive focus in the order they appear in the DOM (Document Object Model). Therefore, when creating web content, it is important to consider the order of the content in the DOM. To account for this in the code, that renders the visualizations, care was taken to first insert general layout elements of the visualizations into the DOM, such as for instance the axes. This way they will be encountered first. Then afterwards the data points are inserted. Here it was again important to insert them in the order that they appear in the chart from left to right. This means that e.g. the data point for 1950 is inserted into the DOM before the data point for 1951. This way a sensible focus order for keyboard and screen reader users was achieved.

**Skip link** A skip link was included, that allows screen reader and keyboard users to bypass and skip over the visualization, so that they don't have to tab through every data

point in order to get to e.g. the data download. This was done as it was suggested in recommendation 4.1.9.

#### 5.4.10 Fullscreen view

Recommendation 4.1.15 states that visualizations should work well with browser zoom and assistive technology for zooming. This criteria should already be satisfied through the responsive design of the prototype website. However, additionally a zoom functionality for the visualizations was provided to see, whether this might be helpful for people with usable residual vision. This was implemented by adding sub pages to the main visualization pages where the user can view the visualization in a fullscreen view. The user can get to this view by clicking on the “Enlarge diagram” button below the visualization. They are then taken to a page that only consists of the visualization and buttons for configuring the zoom level of the visualization. This fullscreen view of the bar chart can be seen in figure 5.7. This view also includes the overview and trend descriptions for screen readers, as well as the screen-reader accessibility of the elements within the diagram. Other accessibility features such as the data download and the sonification are not available in this view.

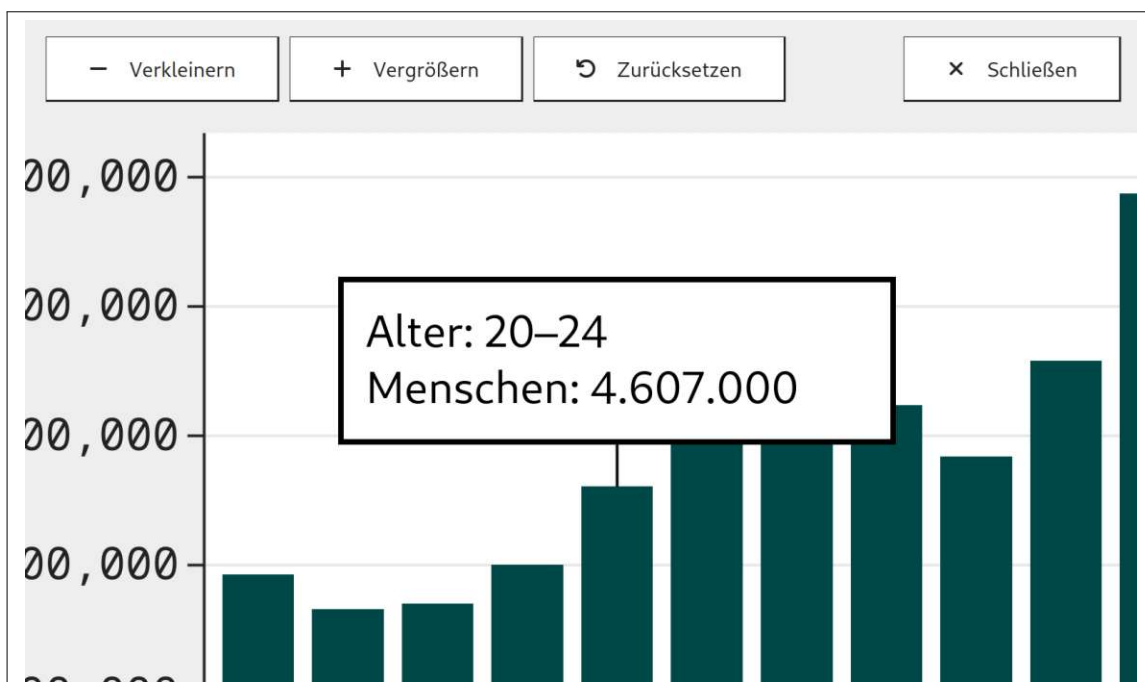


Figure 5.7: The fullscreen view of the bar chart in a strongly zoomed-in state. The buttons are labeled (from left to right) “zoom out”, “zoom in”, “reset” and “close”.

The fullscreen view generally used the implementation of the visualization from the main visualization page. Event listeners were added to the zoom buttons that would then trigger a function for dynamically changing the size of the entire visualization by

changing the values of specific CSS properties related to size. The function that updates the zoom level after a button was clicked can be seen in listing 6.

```
/**
 * Zoom the viz elements so that it corresponds with
 * the current zoom state.
 *
 * @param zoomState - the current zoom state
 * @param visualizationElement - the element that needs
 * to be zoomed to match the state
 */
function updateZoomLevel(
  zoomState: ZoomState,
  visualizationElement: HTMLElement
): void {
  if (zoomState.isReset) {
    visualizationElement.style.minWidth = '';
    visualizationElement.style.maxWidth = '';
    visualizationElement.style.width = '';
  } else {
    const defaultWidth = measureDefaultWidth(
      visualizationElement
    );
    visualizationElement.style.minWidth = 'initial';
    visualizationElement.style.maxWidth = 'initial';
    visualizationElement.style.width = `${
      zoomState.zoomLevel * defaultWidth
    }px`;
  }
}
```

Listing 6: The function for updating the zoom level of the fullscreen view.

#### 5.4.11 Data table

Per recommendation 4.1.13 the data from the visualization should be offered in the form of a table. This is why data tables were included in the prototype. For each visualization the data table is placed on its own page. A link to this page is below the visualization. An example for one of the two tables can be seen in figure 5.8. Because of time constraints during prototype development the table was not made sortable or filterable, even though this would have ideally been included according to recommendation 4.1.13.

The base structure of the table is already included in the base HTML of the table pages. The entries in the table are dynamically generated and appended to the DOM



← Zurück zum Diagramm

## Prototyp 2 – Tabelle: Zahl der Geburten und Sterbefälle pro Jahr in Loremland

Zahl der Geburten und Sterbefälle pro Jahr in Loremland von 1950 bis 2021

Jahr	Geburten	Sterbefälle
1950	1.116.701	748.329
1951	1.106.380	752.697
1952	1.105.084	767.639
1953	1.095.000	780.000

Figure 5.8: The table for the line chart with three columns “year”, “births” and “deaths”.

(document object model). Listing 7 shows the base HTML of one table and listing 8 shows the TypeScript code that generates the table entries from the data. To make the table more accessible, a `caption` is added within the table and the `scope` attribute is used so that screen readers can associate the correct column heading with the entries.

#### 5.4.12 Data download

Per recommendation 4.1.14 a download of the data is offered to the user. This was realized as the option to download the CSV file containing the data via a link that is placed beneath the visualization. The implementation can be seen in listing 9 and an example for the offered CSV file in listing 10.

#### 5.4.13 Sonification

Recommendation 4.1.6 states that it needs to be possible to get an overview of the data in a non-visual way. In addition to the overview and trend descriptions (see section 5.4.7) a sonification was included to allow the user to listen to an audio version of the data where each data point is mapped to a sound. This feature is experimental and was suspected to not be useful for solving any tasks in the study yet. However, it was still included as an artifact that can be used to discuss with the participants possible future

```

<table class="table">
  <caption>
    Zahl der Geburten und Sterbefälle pro Jahr in Loremland von 1950
    bis 2021
  </caption>
  <thead>
    <tr>
      <th scope="col">Jahr</th>
      <th scope="col">Geburten</th>
      <th scope="col">Sterbefälle</th>
    </tr>
  </thead>
  <tbody id="data-table"></tbody>
</table>

```

Listing 7: The base HTML of one of the tables.

```

const numberFormatter = Intl.NumberFormat('de-DE');

/**
 * Renders a table with the given population data
 *
 * @param data - the population data
 */
const drawTable = (data: BirthsDeathsDatapoint[]): void => {
  const svg = d3.select('#data-table');
  const rows = svg.selectAll('row').data(data).join('tr');
  rows.append('td').text((d) => d.year);
  rows
    .append('td')
    .text((d) => numberFormatter.format(d.births));
  rows
    .append('td')
    .text((d) => numberFormatter.format(d.deaths));
};

```

Listing 8: The TypeScript code that generates the table entries.

adaptations and whether a feature like this might become useful to them in the future. The sonification feature of the line chart can be seen in figure 5.9.

**How it works** In the sonification data points are mapped to sounds. Users can press play on a button, in order to start and stop the sonification. In the sonification, what is

```

<p>
  <!-- Translation: "Download the data as CSV file." -->
  Lade die
  <a download href="/birth_death_rate.csv">Daten als CSV-Datei</a>
  herunter.
</p>

```

Listing 9: The implementation of the CSV download.

```

id,age_group,population_size
0,0-4,3927000
5,5-9,3662000
10,10-14,3702000
[...]

```

Listing 10: The CSV file from the bar chart “population\_by\_age.csv”.

on the x-axis of the visualization is mapped to the dimension of time instead. So the first played sound corresponds to the first, left-most value on the x-axis and the last sound corresponds to the last, right-most value. What is on the y-axis is mapped to pitch. The higher the pitch of the sound, the higher the value, the lower the pitch, the lower the value. Every data point is represented by one sound.

For the bar chart, there is one sound for each age group. The higher the sound, the more people are in the age group. The lower the sound, the less people are in this age group. The sounds are played starting in ascending age order, starting with the youngest age group 0 to 4 and ending with the oldest age group 95 to 99.

For the line chart the user can switch between listening to the births data series, the deaths data series or both at the same time. When choosing to listen to both at the same time, there are two sounds for each year, that are playing in fast succession. The first one represents the number of births in that year. The second one represents the number of deaths in that year. The higher the sound, the higher the number of births or deaths. The lower the sound, the lower the number of births or deaths. The sound pairs are played in ascending chronological order, starting with 1950 and ending with 2021. When the user chooses to only listen to one of the data series, only one sound is played per year.

**Implementation** As stated in section 3.2.4 the sonification was implemented using the JavaScript libraries Tone.js and d3.js. First d3.js was used to create a scale function that maps data values to pitch. This can be seen in listing 11.

This function for mapping values to pitch is then used in the function that creates the sequence of notes for the sonification. This function can, depending on whether the parameter `secondDataSeries` is passed when calling it, create a tone sequence for one data series or two data series (births and deaths in the line chart). This function can be

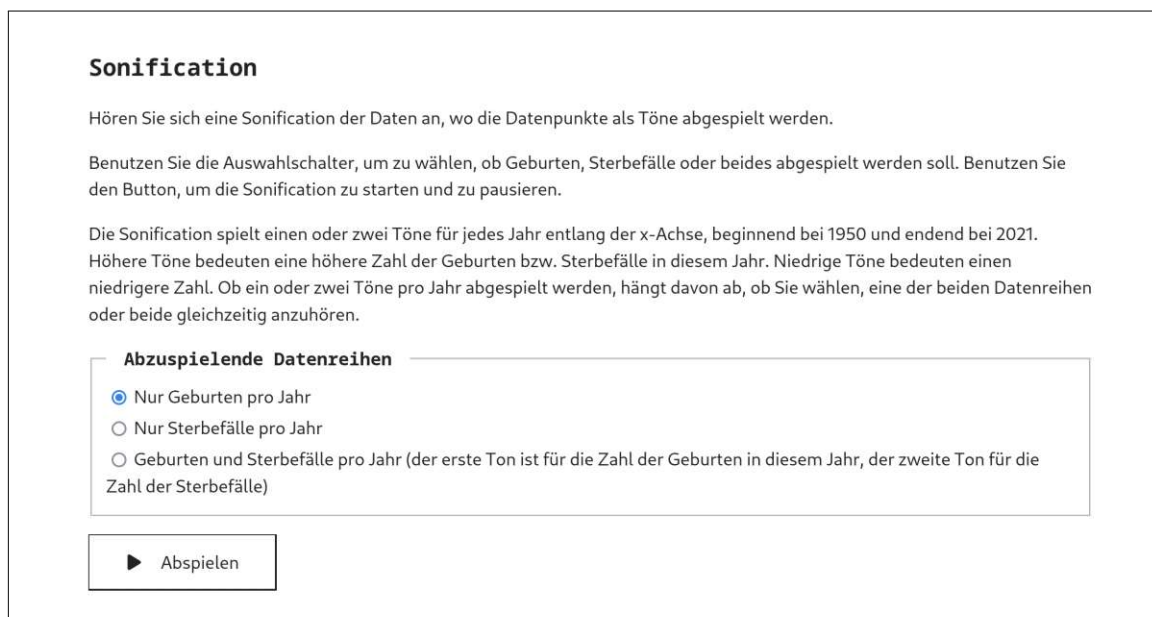


Figure 5.9: The sonification feature of the line chart. At the top a text explains how to use the feature. Below the user can choose which data to listen to and press play or pause.

```

const smallestValue = Math.min(...dataForSonification);
const largestValue = Math.max(...dataForSonification);

const toneScale = d3
  .scaleLinear()
  .domain([smallestValue, largestValue])
  .range([200, 1000]);

```

Listing 11: The code that creates the scale for mapping values to pitch.

seen in listing 12. The playing, pausing and changing of the sequence is then controlled by the play-pause-button and for the line chart additionally by the radio buttons that allow the user to select which data to listen to.

```

/**
 * Creates the sequence that determines when which note
 * will be played
 *
 * @param data - the data to create the sequence from
 * @param secondDataSeries - an additional series of
 * data points

```

```

* @param toneScale - the scale for mapping data
*   points to notes
* @param resetPlayer - function for resetting
* the player at the end of the sequence
* @returns sequence - the created sequence
*/
const createSequence = (
data: number[],
secondDataSeries: number[] | null,
toneScale: d3.ScaleLinear<number, number, never>,
resetPlayer: () => Promise<void>
): Tone.Sequence<any> => {
  const dataAsNotes = data.map((datapoint) =>
toneScale(datapoint)
);
  const synth = new Tone.Synth().toDestination();
  let secondDataAsNotes: number[];
  if (secondDataSeries) {
    secondDataAsNotes = secondDataSeries.map(
(datapoint) => toneScale(datapoint)
);
  }
  const durationOfOneUnit = secondDataSeries ? 1 : 0.5;

  let index = 0;
  const sequence = new Tone.Sequence(
(time, note) => {
    synth.triggerAttackRelease(note, 0.1, time);
    if (secondDataSeries) {
      synth.triggerAttackRelease(
secondDataAsNotes[index],
0.1,
time + 0.2
);
    }
    if (index === dataAsNotes.length - 1) {
      resetPlayer();
    }
    index += 1;
  },
dataAsNotes,
durationOfOneUnit
);

```

```
Tone.Transport.loop = false;  
sequence.loop = false;  
  
    return sequence;  
};
```

Listing 12: The code that creates the tone sequence for the sonification.

### 5.5 Summary

This chapter presented the prototype that was developed as a part of this work. The prototype was created in the form of a website with two data visualizations. The accessibility of the visualizations was implemented according to the synthesized recommendations from chapter 4. Different ways to engage with the visualization were provided, including screen reader accessibility of the visualization itself as well as alternative ways to access the data e.g. via a data table. The next chapter will report the results from an evaluation of the prototype with blind or visually impaired persons.

# Prototype evaluation results

In order to assess the prototype, a formative evaluation with five blind or visually impaired persons was conducted. Each study session consisted of two parts. In the first part, the participant was asked to fulfill tasks using the prototype. The second part was a structured interview about the prototype. For a detailed description of the methods used, please refer to chapter 3.

This chapter presents the results of the study. The first section (6.1) describes how the participants solved the tasks and which issues arose while they worked on the tasks. The second section (6.2) summarizes the replies of the participants during the structured interview. Section three (6.3) describes any interesting observations and remarks that did not strictly fit into the other parts.

Note that the gender neutral singular pronoun “they” is used in this chapter to refer to singular participants. This is done in order to protect the privacy of the participants.

## 6.1 Results of the tasks

In the task part of the study the participants were asked to solve different tasks using the prototype. This section describes, task by task, how the participants solved the tasks and which issues were encountered while working on the tasks. Table 6.1 gives an overview of how many participants were able to solve each task and how many of them asked to be given the answer options. As visible in the table, most tasks were solved by the participants. In some cases, however, participants asked to be given the possible answer options or gave a wrong answer while working on tasks of the type “Finding a data point with a specific property”.

### 6.1.1 Task 1: Reading the value from a given location in the bar chart

**Question** “What is the number of people in the age group 40 to 44 years?”

Answer was...	...correct		...wrong	
	without	with	without	with
Answer options:				
<b>Task 1: Reading value from given location</b> (bar chart)	5	0	0	0
<b>Task 2: Finding a data point with a specific property</b> (bar chart)	4	0	1	0
<b>Task 3: Describing trend of data in specific part</b> (bar chart, answer options given by default)	-	5	-	0
<b>Task 4: Reading value from given location</b> (line chart)	5	0	0	0
<b>Task 5: Finding data point with specific property</b> (line chart)	2	2	1	0
<b>Task 6: Finding data point with specific property</b> (line chart)	3	1	1	0
<b>Task 7: Describing trend of data in specific part</b> (line chart, answer options given by default)	-	4	-	1

Table 6.1: Correct and incorrect answers with and without answer options given by task.

**Overview** All participants correctly solved the task. No one asked to be given the three answer options.

**How it was solved** One participant solved the task by finding the value in the table using their screen reader. Three participants solved the task by identifying the correct bar in the visualization and reading its tooltip using their screen reader. One participant used the fullscreen view and solved the task using their residual vision. In a zoomed-in state they navigated along the x-axis until they reached the bar that belongs to the needed group, then navigated upwards along the bar until they reached the tooltip and visually read the answer from it.

**Issues** No issues were found during this task.

### 6.1.2 Task 2: Finding a data point with a specific property in the bar chart

**Question** “What is the largest age group?”

**Overview** Four participants correctly solved the task. One participant gave a wrong answer, choosing the next older group from the correct one. No participant asked for the answer options.

**How it was solved** Two participants solved the task by first listening to the trend description, where they heard that the largest groups are around age fifty to sixty. They



then navigated into the visualization, where they compared the values of the bars “50 - 54” and “55 - 59” and picked the larger one. One participant solved the task by listening to the overview description, which directly states the largest and smallest data points. One participant used the fullscreen view to solve the task visually. They first zoomed out using the zoom-out button on the page to see where the tallest bars are. Then they zoomed in on the peak using their zoom software, identified the largest bar, and read the age group from the tooltip.

**Issues** The participant who answered wrongly was using the screen reader to compare the values of the bars within the visualization. They read the values from the tooltips using the screen reader and chose the group that follows after the correct group. The participant stated that they were confused about whether the age group or the population size is read first and thus not being sure which population size belongs to which age group.

The participant who solved the task by listening to the overview description remarked that they were only able to solve the task by chance since the maximum was stated in the overview description. They stated that if they had been asked e.g. for the second largest value, they would not have been able to answer. They stated they would need the ability to sort the table to answer these kinds of questions.

### 6.1.3 Task 3: Describing the trend of the data in a specific part of the bar chart

**Question** *“How could one describe the data in the age ranges from 10 to 34 years?”*

#### Answer options

- *“Generally, the number of persons per group is very similar in this area.”* (wrong)
- *“The older the group, the larger. The largest group is the group of the 30- to 34-year-olds.”* (correct)
- *“The older the group, the smaller. The largest group is the group of the 10- to 14-year-olds.”* (wrong)

**Overview** All participants chose the correct option. Answer options were given to the participants right away as part of the task.

**How it was solved** This task was solved by the participants in various ways. One participant compared the values in this age range in the table using their screen reader. One participant used their screen reader to listen to the bars in this range in the visualization. One participant remembered hearing something about this in the trend description, used the screen reader’s search function to jump to the trend description, then listened to the trend description and part of the overview description. Afterwards

they listened to the values of the relevant bars in the visualization using the screen reader. One participant used their residual vision to solve the task: They zoomed in on the x-axis to identify the relevant bars and then navigated up to see the tops of the bars and understand the trend. One participant used their residual vision to see the trend and used their screen reader to listen to some of the bars in the visualization to confirm what they saw.

**Issues** No issues were found during this task.

### 6.1.4 Task 4: Reading the value from a given location in the line chart

**Question** “*What is the number of births in 2003?*”

**Overview** All participants correctly solved the task. No one asked to be given the three answer options.

**How it was solved** Two participants solved this task using their screen reader to read the value of this year from the table. Two other participants searched for “2003” using their screen reader search and jumped to the tooltip of this year and found the answer there. One participant used the fullscreen view and their residual vision: First they zoomed in on the x-axis to get to the right year, then they navigated up to read the data from the tooltip.

**Issues** No issues were found during this task.

### 6.1.5 Task 5: Finding a data point with a specific property in the line chart

**Question** “*In which year is the number of births the largest?*”

**Overview** Four participants solved the task correctly. Out of those four, two asked for the answer options. One participant answered wrongly, choosing a year adjacent to the correct year. They did not ask for the answer options before answering the question.

**How it was solved** One participant listened to the overview description and found the answer there.

One participant first listened to the trend description, which does not contain the answer, and then used their screen reader to skim-read the data points in the visualization from start to end. They always skipped a few data points and then listened to a tooltip of the current year and number of births and then skipped a few ahead again. When they identified the area around the peak they listened more closely and correctly identified the largest value.

One participant directly stated that this task was not solvable for them without any answer options. After receiving the answer options they directly chose the correct answer without any further actions. After being asked how they knew this, they stated that they used prior knowledge and chose the only option that seemed plausible to them.

One participant first tried to find the answer using the screen reader search, which did not return any results. Then they skim-read the overview and trends descriptions, but skipped the part that would have contained the answer. They then asked for the answer options and switched to the table. While being read the answer options they checked the respective value in the table and chose the largest of the three, which is the correct answer.

**Issues** The participant who answered wrongly used their residual vision and the full screen view. They first zoomed out to see the shape of the data and then zoomed in on the correct line, tracing it from start until they found the peak. At the peak they compared the values of two points of similar height by reading the values from the tooltips. They chose the wrong year since they compared the number of deaths and not the number of births between those two data points at the peak.

One participant noted, that they wish the table was searchable. Another participant also wished for the table to be searchable and sortable, so that they could solve the task with the table. They also noted that the sonification would be of no help either since they tried it earlier, and it does not allow them to understand at what year the peak is.

One participant stated that they used prior knowledge about population data to pick the right answer. They claimed that the birth rate would have a similar shape in countries around the world, meaning, that they could use their prior knowledge regardless of which country the data in the chart belongs to. This points to an issue in the study design. In the prototype, it was stated multiple times that the data belongs to a fictional country. The idea was, that this would prevent participants from drawing on prior knowledge to solve tasks. In this case, however, the measure did not suffice.

One participant listened to the overview and trend descriptions, but skipped the part where the answer would have been. They claimed, that they don't want to listen to the whole text, since it would take too long. Another participant listened to the full trend description, but not the overview description, where the answer would have been.

### 6.1.6 Task 6: Finding a data point with a specific property in the line chart

**Question** *“What is the first year in which the number of deaths is higher than the number of births?”*

**Overview** Four participants solved the task correctly. Out of those four, one asked for the answer options. One participant answered wrongly, choosing a year adjacent to the correct year. That participant did not ask for the answer options.

**How it was solved** One participant listened to the trend description and found the answer there. One participant searched for a relevant keyword on the page using the screen reader search, skipped to the search result in the trend description and answered correctly. Another participant first listened to the overview description and then to the trend description and found the answer in the latter.

One participant asked for the answer options right away, stating that they would not know how to solve it otherwise. They compared the given options in the table using their screen reader and answered correctly. They stated that a search function would have been useful for quickly finding and comparing the three given options.

**Issues** One participant used their residual vision to locate the point where the lines cross and read the answer from the tooltip. They erroneously chose the data point right before the lines cross instead of the point right after the lines cross. This might also have been due to misunderstanding of the question.

### 6.1.7 Task 7: Describing the trend of the data in a specific part of the line chart

**Question** “*What’s the general trend of the birth rate between 1997 and 2011?*”

**Answer options**

- “*It is falling slightly.*” (correct)
- “*It is increasing slightly.*” (wrong)
- “*It fluctuates slightly, but is generally stable.*” (wrong)

**Overview** Four participants answered correctly. The answer options were given right away as part of the task. One of the participants stated, that the answer options were not satisfactory and wanted to first choose a wrong option, but then changed their mind and chose the correct one. One participant answered wrongly, but expressed, that they were not sure about the answer.

**How it was solved** Two participants used their residual vision to see the shape of the line and correctly solved the task this way. One of them probed a few data points in the relevant part of the visualization using their screen reader.

One participant first listened to the trend description and then the overview description. Then they tried to download and open the CSV file in a spreadsheet software, but they could not get the data to be correctly displayed (the entire data of one row ended up in the first cell of that row) and abandoned this approach. They then returned to the visualization. They searched for a year in the relevant range with their screen reader’s search function, jumped to that part of the visualization and listened to the data points in this area. Then they chose the correct answer.

One participant opened the table and listened to the relevant entries using their screen reader. They stated that they found none of the answer options satisfactory, but then chose the correct one.

**Issues** One participant used the screen reader search to jump to the relevant part of the data visualization and listened to the data points in that part. They then chose the wrong answer option “The number of births varies slightly, but is mostly stable.” They stated, that this task is hard for them, since the range of relevant years is large and since the numbers they are comparing are also large, which made it hard for them to do the task. They stated, that they would have to listen to the data one more time, if they would be required to answer with absolute certainty.

One participant, who answered correctly, stated that the answer options were not adequate in their opinion. They explained that they heard with the screen reader, that the number was almost always decreasing from one year to the next, but that there were a few exceptions, which is why they would not agree fully with the correct option “The number of births is slightly decreasing.” They stated, they would have described the trend in this part of the data as “The number of births is mostly falling, but not so strongly since in some years the trend reverses.”

## 6.2 Results of the interview questions

After the task part of the study a structured interview about the prototype was conducted. This section summarizes and describes the answers of the participants question by question. Note that, as stated in section 3.3.5, not only the direct reply to each question was included in the summary. Additionally any statements made during the session that related to the respective interview question were included in the summary.

### Question 1: Usability in comparison to other websites

*“In general, would you say the usability of these diagrams was better, worse of similar for you, compared to other diagrams you encounter on websites?”*

All participants stated that the diagrams in the prototype were more usable than diagrams they encountered on other websites. One participant stated, that the diagrams in the prototype were better than the ones on other websites in almost every regard. Another one said, they found the diagrams in the prototype very usable. One participant noted that on other pages they usually have trouble accessing the data that is depicted in diagrams. Another participant similarly stated, that they usually avoid diagrams on other websites.

### Question 2: Useful and liked features

*“Which features of the diagrams were especially useful to you? Which parts of the prototype did you especially like? And for which reasons?”*

The participants mentioned various features they liked. Three participants mentioned the table and the CSV download as features they liked. One participant even referred to the table as their “favorite list” while using it and another one said they had fun using the table since it was implemented accessibly, which made it pleasant to use. Generally, the possibility to access the actual data was appreciated. One participant stated that the trend description was the most important feature to them to get an overview, and furthermore the access to the individual data points in the visualization was useful to them for understanding the details. One participant also mentioned that, in addition to the table and the CSV download, they liked the sonification as something new to them. One participant who did not use a screen reader and relied on their residual vision alone highlighted that they liked the fullscreen view with the ability to zoom in and out. They also liked that the tooltips contained all the data so that they would not need to navigate back and forth between the data point and the axes to read out the values while being in a highly zoomed-in state.

### Question 3: Features that were not liked or had issues

*“Which features of the diagrams were not useful, not understandable or not easily usable? Which parts of the prototype did you not like and for what reasons?”*

The feedback on parts that were deemed not easily usable, not useful or not understandable was highly individual and there were no points that were named by more than one participant.

The participant who relied on their residual vision alone criticized, that in the bar chart the tooltip was displayed above the bar and not at the point of the bar where they were currently with their cursor. Thus, when they were on a highly zoomed-in state, they often had to first navigate up to the top of the bar in order to see the tooltip.

Another participant stated that the sonification was not useful to them.

While navigating the data points in the visualization with their screen reader another participant experienced confusion about which order the values are read in and whether the year or age group belongs to the value being read before or after it. This happened since they can't see in which order the data is listed in the tooltip and since there is no indication when they are leaving one tooltip and entering the next. They also noted, that they didn't like, that once they started navigating through the data points within the visualization, there was no easy way for them to jump out of the diagram again, but that they had to navigate through all remaining data points first to get to the end.

Another participant criticized that their screen reader announced the visualizations as “illustration”, which means to him that it is purely decorative and does not carry any meaning. This also prevented them from using the keyboard shortcut for navigating between images on a website since the visualization was not identified as an image. They also criticized that the column heading labels in the table were too long since they are read out by the screen reader quite often. They also found that the overview and trend descriptions were too long and interpretative. They would have preferred a much

shorter description, that would only announce the presence and topic of the visualization, but not contain any information about the structure or the data. They suggested that the visualization would be implemented as a link to the raw data and that the image description would be kept very brief. The participant was asked about their thoughts on having a very short image description and a link to a longer image description. They stated that they would not want this longer description.

One participant criticized that the dashes at the start of each row in the tooltips were slowing them down while navigating through the data points in the visualization with their screen reader. However, they noted that this might not be an issue for users whose screen readers do not read out dashes and that it might be difficult to please everyone. Generally navigating between the tooltips of the data points was cumbersome for this participant. The tooltips were a little too verbose for them and they would prefer if instead of “year: 2011” it would be written just “2011”.

#### Question 4: Surprise and novelty

*“Was there anything new or surprising about the diagrams?”*

When asked about new or surprising elements of the prototype every participant named something else. Two participants stated that the sonification feature was new and surprising to them. Another participant stated that they were pleasantly surprised about the table. They noted that it is not easy to implement an accessible table and that they were pleasantly surprised that the table was accessible to them. One participant who was using a combination of their residual vision and a screen reader, stated, that they were surprised that they were able to access the data points inside the visualization with their screen reader. Another participant who was relying on their residual vision alone noted, that the tooltip containing all relevant data was new to them. They also stated that in the line chart it was new to them, how they were helped with orientation by the circles and the long vertical line that highlights the currently selected year and data points.

#### Question 5: What was missing

*“Is there anything you were missing? Is there anything you would have wished for so that the diagrams would be more usable.”*

Two participants wished for the ability to sort the table. One of them also wished that there would be a search function to filter the table. The other one additionally wished for more columns with meta data that would display e.g. the difference between births and deaths in that year (in the table for the line chart), the relative size of the current population group compared to the total population in percent (in the table for the bar chart) or a column that would display by how much value of the current row differs from the value in the previous row.

One participant stated that in the sonification they were missing the ability to know the relative highness of the pitch of the current sound. They missed a frame of reference

to compare the pitch of the sounds to. But when explicitly asked, all participants found some points that were lacking in the sonification, which is described in the following section.

One participant also noted that they think it might make sense to ask screen reader users first whether they would like to enter the visualization and browser the individual data points, before making them available. But they expressed not being sure about whether this would be a good idea.

One participant who was extensively using the overview and trend descriptions stated that they would prefer, if the trend description was a bit more detailed. They were asked how they would like it, if there was a short description and then a link to a longer, detailed description since this was the suggestion of another participant. But this participant preferred for the description to stay in the same place as it already is, but for it to just be a bit more detailed. The participant also suggested numbering the bars in the bar chart for better orientation and turning the year (in the line chart) into a heading, so that they could more easily jump from tooltip to tooltip by using their screen reader command for jumping to the next or previous heading.

The participant who was relying on their vision alone noted, that in the fullscreen view they would have preferred to navigate around the visualization using their cursor instead of being forced to use scrolling or the scrollbars while in a highly zoomed-in state. They also asked whether it would be possible to make the light gray vertical line in the line chart slightly darker.

### Question 6: Thoughts on the sonification

*“What are your thoughts on the sonification? Was it useful? Could you imagine that something like this would be useful in diagrams on actual websites?”*

All participants had some criticisms about the sonifications and expressed their thoughts on how to improve it. Since these ideas varied between participants, the statements regarding the sonification are summarized by participant.

One participant stated that the sonification would be useful for sure since in their opinion, the more ways there are to access the data, the better. They stated that the idea is not bad, but that currently it's hard to understand, where you are in the sonification while it plays. They stated, that it's easy to get lost after hearing a few beep sounds. According to them, something would be needed to help the user understand where they are right now in the x-dimension e.g. the year, and around which height they are in the y-dimension e.g. whether the current beep sound stands for a high, low, or medium number of births in that year. They also stated that especially in older age lots of people hear badly and that it might be difficult for them to use the sonification

One participant similarly stated that they liked the idea of the sonification, but that the way the feature is implemented would need to be improved. Their criticism, however, went into a very different direction. For them the sonification was way too slow. They would like to use the sonification as a way to get a first impression of the data. They would not try to extract singular data values from it. They complained that the tones



sounded too much like music. They would prefer, if, instead of singular beeping sounds, there would be one continuous sound that would change pitch according to the changes in data value. Furthermore, the participant noted, that they liked that in the sonification for the line chart they were able to choose whether to listen to one of the data series or both at the same time.

Another participant had complaints that were similar to the complaints of both participants whose experiences were described above. They generally found the sonification interesting, but in its current state not useful and more of a fun gimmick. They found it too long and also lost orientation. They stated it was difficult to tell the pitch of the sounds apart. They suggested that the current position on the x-axis e.g. the year would be announced while the sonification runs, so that they would not lose orientation after a few beeps. They also suggested making the sonification more music-like and turning the singular beeps into one constant sound that changes pitch over time with the change of the data values. The participant stated, however, that they were still skeptical about this feature becoming actually useful.

Another participant similarly did not find it useful and also called it just a gimmick. However, they stated, it could become useful, if the implementation was done better. They similarly to other participants struggled with losing orientation e.g. which year they are in right now. They would also like, if the current year or age group was announced.

The participant who relied on their vision alone was very confused by the sonification and stated that they did not understand, what they were hearing while the sonification played. To them it sounded like music and they were not sure what was causing the change in pitch in the beep sounds they were hearing. After receiving an explanation of what they were hearing, they made some suggestions for improving the sonification. They stated that they would prefer, if the sonification was directly connected to the visualization. For instance, they said they would like to trigger the sound by using the mouse or keyboard directly at the data points inside the visualization. Furthermore, similar to other participants, they struggled with a lack of orientation. They stated they were missing reference points with regards to the year they were currently at and whether the current tone meant a large or a small number. The participant concluded that the sonification was an interesting idea, but that they personally would not use it, even if it was implemented in a better way.

### Question 7: Feature to take home

*“If you could pick one feature of this prototype that would then become available in the future in the diagrams on other websites, what would you choose?”*

Three participants replied, that they would like to have the table for diagrams on other websites, too. One of those three added that the table should be searchable and sortable. Another one of them mentioned that they would pick the table and the data download.

Another participant stated that they would pick the trend descriptions and the ability to access the individual data points in the visualization.

The participant who relied on their vision alone stated that they would pick the comprehensive tooltips and the fullscreen view with the buttons for zooming in and out.

### 6.3 Additional observations and remarks

During the sessions there were some interesting remarks and observations that fit neither into the analysis of the task part, nor into the analysis of the structured interview part. These occurrences are summarized in this section.

#### 6.3.1 VoiceOver not reading numbers correctly

With one participant, who was using the VoiceOver screen reader, a bug occurred in which VoiceOver kept reading numbers wrongly. For instance, the number “706,721” was read by VoiceOver as “7.621”. This seemed to affect all numbers lower than one million. This issue was discussed with the participant during the study and the correctness of the answers given by this participant was evaluated after correcting for the effects of this bug.

#### 6.3.2 Screen reader settings for reading numbers

The screen reader of one participant was reading all numbers out letter by letter. Instead of reading for instance “three hundred twenty six thousand four hundred sixteen”, it would read out “three two six four one six”. The participant stated that this was due to their settings and that they tried to set up the screen reader setting correctly before the study, but that they did not succeed.

#### 6.3.3 Overlooking the overview and trends descriptions

The participant who was using a combination of their residual vision and a screen reader encountered the unique issue, that they did not notice the presence of the overview and trend descriptions. These descriptions were included with the intention of them being like alt texts (image descriptions) of images and were thus included at the start of the visualization in a way that they were not visible. The participant’s screen reader always draws a rectangle around the element that is currently focused and being read out. When the descriptions were read out, only a small rectangle was drawn at the start of the visualization. The participant stated that they saw it was only a tiny rectangle and skipped over it, since they assumed it couldn’t be anything extensive or important. As a result they did not know about the existence of the overview and trend descriptions and were not able to use them during the tasks. The participant wished that the overview and trends descriptions would be visible on the page and possibly more structured, so that they would be easier to navigate with a screen reader.

#### 6.3.4 Usefulness of the fullscreen view

The participant who relied on their vision alone was asked, whether the fullscreen view of the chart with the zoom in and zoom out buttons was useful to them, even though they were already using their own zooming software. They stated that they liked the feature and they used it in combination with their own zooming software since they would complement each other.

#### 6.3.5 CSV as file format not ideal

One participant noted that offering the data in the form of a CSV file was probably not ideal for most people. They stated that they themselves knew what a CSV file is and how to open it, but that most other people would probably struggle with a CSV file. However, they generally liked that a data download was available and their criticism only concerned the file format.

#### 6.3.6 Visibility and length of explanation texts

The explanation text for how to use the visualization was criticized by one participant. They stated that it was too long and detailed. They also criticized that part of it was not relevant to them and another part was relevant to him, but not to people who don't use a screen reader. They suggested, that the explanation regarding tooltips and other graphical features should be hidden from screen reader users and that the explanations regarding the use of the visualization with a screen reader should be visually hidden from sighted people.

#### 6.3.7 Tooltip staying open while hovered

The participant who relied on their vision alone was irritated that in the line chart they were not able to switch between data points by moving the cursor left and right while the cursor was on the tooltip of the current data point.

#### 6.3.8 Comparison between the visualizations

One participant noted that they found the line chart harder to use since they had to compare three values (year, number of births, number of deaths) as opposed to two (age group, size of age group) in the bar chart.

Another participant noted that they prefer the line chart since they found the layout easier to follow. When they were telling this, they were navigating the tooltips with their screen reader. The line chart has a dash at the start of each line in the tooltip, which the bar chart does not have.

### 6.3.9 Perception of the data points as list

Two blind participants did not know that they were navigating the individual data points and tooltips inside the visualization with their screen reader. They thought of this part of the page as something like a list that would be located below and not inside the visualization.

### 6.3.10 Empty table for one participant

For one participant the screen reader was not able to access the content of the table at all. The screen reader read out the title and the column headings of the table, but claimed that there were no entries, even though the entries were displayed on the page. This issue was particularly strange since other participants had applauded the table for being implemented in a way that made it very accessible and pleasant to use. The participant stated that they generally don't often use tables and that they think that tables work better with other screen readers.

### 6.3.11 Navigation with the tabulator key

One participant noted that they prefer to navigate through the visualization using the arrow keys, even though the instructions above the visualization recommend the use of the tabulator key. The participant stated that they used the arrow keys as they prefer those.

### 6.3.12 Feedback not concerning the visualizations

Some participants commented on aspects of the page that were not part of the visualizations. For instance, one participant did not like that the start page with the links to the two visualizations already ended after the second link. There were not many complaints about these kinds of things and since they do not concern the subject of the study, this will not be evaluated.

## 6.4 Summary

This chapter has presented the results of the prototype evaluation. The visualizations in the prototype turned out to be generally usable and accessible. This can be seen in the statements of the participants in the interviews and is also confirmed by most tasks being solved by the participants. The study showed that the participants differed in their preferences and in their ways of solving the tasks. One feature that was appreciated by multiple participants was the data table. Participants, however, wished that the table would be sortable and filterable or searchable. Some participants employed skim-reading techniques to find specific data points or pieces of information in the textual description. The support for this kind of interaction by the prototype was, however, limited. One point in which all participants agree was, that the sonification was not useful, often

quoting a lack of orientation as an issue. A more in-depth discussion of the study results, as well as the results of the other parts, is given in the following chapter.



Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar  
The approved original version of this thesis is available in print at TU Wien Bibliothek.

# CHAPTER 7

## Discussion

This work explores the question of how existing knowledge from previous research can be used to create web-based visualizations that are accessible to persons who are blind or visually impaired. As a first step towards answering this question, previous literature was examined to identify what recommendations have already been made by other researchers in the field. This first step of the work specifically addressed the question:

*“RQ1: Which recommendations have been made by researchers with regards to creating web-based data visualizations that are accessible to blind and visually impaired persons”*

Even though data visualization accessibility is a field that has not been extensively researched, a few works could be identified that contained recommendations in this regard. Some of these works were catalogs of testing criteria for visualization accessibility [Ela22, AMTGS21], while others were user studies [SFK<sup>+</sup>21, SCWR21], literature analyses [KJRK21], technical explorations [WOH<sup>+</sup>15, Str21a] or practical suggestions [Str21b]. The recommendations from these works were synthesized into a set of 19 recommendations (see chapter 4). The recommendations were then used to create a prototype with web-based data visualizations (see chapter 5) to answer the question:

*“RQ2: How can these existing recommendations be translated into the design and implementation of a web-based data visualization?”*

The prototype was created using common methods and tools for creating interactive data visualizations for websites. Two visualizations were developed while following the synthesized recommendations from the previous step. Not all recommendations could be followed, but they were followed as much as the implementation of a prototype allowed. Following the guidelines was sometimes difficult, as they sometimes provided too little guidance on how to achieve the desired result. But generally, drawing on previous

experience and using experimentation, it was possible to create accessible visualizations using the recommendations. The resulting prototype was then evaluated with people with disabilities to answer the final question:

*“RQ3: Does a data visualization that is based on current accessibility recommendations prove usable and accessible to actual persons who are blind or visually impaired?”*

In a study involving five blind or visually impaired persons the prototype was evaluated with seven tasks and a structured interview. The large majority of tasks was solved and all participants gave feedback that indicated that the prototype was very usable. This indicated that the synthesis of the recommendations and the implementation of the prototype were a success, as they have passed the test with the target group.

The process of synthesizing the recommendations, implementing the prototype and conducting the evaluation has brought out interesting insights concerning visualization accessibility, its implementation in practice and the need for further work in this area. Key insights will be discussed in individual sections below.

### 7.1 Towards visualization accessibility

Generally, the results of this research show that the used approaches work well. All participants stated that the visualizations in the prototype were more accessible than what they usually encounter on websites. The participants were able to work on the tasks and solved them using various features of the prototype. Tasks that involved finding values with specific characteristics proved difficult for some participants. But there were clear pointers as to how the prototype would need to be adapted in order to better support this. Overall, the feedback about which things about the prototype would need to be done differently was very specific and individual. The only exceptions to this were the need for additional functionalities of the table such as sorting and searching, which was requested by multiple participants, and the issues with the sonification which are discussed in a later section. However, generally the prototype and thus the recommendations it implemented proved successful.

Since the recommendations used in the prototype were based on previous works, it can be stated, that these previous works provided useful guidance. There is truth and value to the recommendations that have come out of previous studies such as by Siu et al. [SFK<sup>+</sup>21] and the guidelines created by researchers such as Frank Elavsky in Chartability [EBM22]. A visualization based on the recommendations that came out of these previous works did prove usable to persons who are blind or visually impaired. Thus, the visualization accessibility field seems to be moving in the right direction with its research and the resulting recommendations.



## 7.2 Multiple ways for varying preferences and needs

Different participants of the study used different features of the prototype to work on the tasks. They also spoke about different features when asked about what they liked and what feature they would like to see on more websites. The only exception here is the data table, which was explicitly appreciated by multiple participants. This diversity in preferences and in feature use indicates that it was valuable to include all these different ways to access the data in the prototype. This confirms the recommendations of previous works of e.g. Sharif et al. [SCWR21] and Siu et al. [SFK<sup>+</sup>21], that have stated the importance of providing access in multiple ways.

The differences in preferences and needs might be partly explained by the different levels of visual impairment of the participants in the study. For instance, one participant who had a usable level of residual vision extensively used the fullscreen view. They were not using a screen reader, but they were using magnification software which they combined with the zoom feature in the fullscreen view. This is, of course, a way of interacting with the visualization, that is not feasible for fully blind users who don't have usable residual vision. Another participant with usable residual vision did use a screen reader but still made extensive use of their vision. This participant especially appreciated that the individual data points inside the visualization were screen reader accessible. This allowed them to e.g. solve the task of finding the maximum by using their sight to see in which areas the bars are the tallest and then use their screen reader to read the values of the bars in this area to identify the bar with the largest value. As pointed out by previous researchers such as Kim et al. [KJRK21] there needs to be further research on how we can design for users with usable remaining vision, such as these participants. Generally, more research is needed on how the needs and preferences of people with different types and levels of severance of visual impairment differ and how data visualizations can be best made accessible to these groups.

Providing multiple ways to access the visualization can also be valuable, since the different features have different advantages and disadvantages and can nicely complement each other. This is something that has previously been pointed out by Siu et al. [SFK<sup>+</sup>21]. Some participants used a combination of different features while working on one task. For instance, when searching for a specific data point it happened that participants listened to the trend description, then entered the visualization with their screen reader and used the knowledge they gained from the trend description to decide in which part of the visualization to look for the answer. Future research might also examine how using multiple features together could be made more convenient e.g. by allowing to skip from one part of the trend description to the part in the visualization that is being described in that part of the text.

Another reason to offer multiple ways would be to make the accessibility of the visualization more robust. For instance, for unknown reasons, the data table in the prototype was not usable with the screen reader of one of the participants. But since the data points were not only made accessible through the table, but also within the visualization, the participant was still able to solve the tasks at the same level as the other

participants. Unfortunately, difficulties with compatibility with assistive technologies are not uncommon, therefore, offering multiple ways can help ensure that at least one of them will work for the user and the technology they use.

### 7.3 Providing a well-implemented table is key

The data table was extensively used and appreciated by multiple participants. One participant enjoyed it so much, that they once called it their “favorite list” while using it. Another participant pointed out, that the table was enjoyable to use, since it was implemented in a way that made it easy to work with when using a screen reader. Therefore, a well-implemented, accessible data table should not be missing in any accessible data visualization solution. This confirms the recommendations of previous works [Ela22, AMTGS21] that data visualizations should include a data table. The statements of the study participants show that it is important to carefully implement the table, so that it can be used well with a screen reader. To achieve this, the correct markup needs to be used. For instance, as done in this prototype (see section 5.4.11), the `scope` attribute should be used to make screen readers associate the correct column heading with the correct value in a data entry. Unfortunately, the table was not accessible at all to the screen reader of one participant and showed up as empty, which could not be explained.

While the table was generally appreciated, multiple participants were missing the function to sort, filter and search in the table. Due to limitations of the prototype, the table did not have any of these features, despite filter and sorting features being recommended e.g. by Chartability [Ela22]. These features were especially missed by participants when solving tasks related to finding the global maximum of the data. This points to the importance of not just including a simple table, but taking the time to implement additional functionality that makes it easier to work with the data.

One participant mentioned missing a frame of reference for how the values were changing from row to row in the table. They suggested that some additional columns could be added that contain data about e.g. the difference of the current row’s value to the previous row’s value. The idea would be, that the additional columns would help the user get a better idea of the trends and changes in the data without forcing them to, row after row, do the calculations and comparisons in their head. This is something that might be experimented with in future research.

### 7.4 Textual descriptions are hard to get right

Textual descriptions are something that have long been used to make images accessible to blind and visually impaired internet users. Thus they are something very familiar to blind and visually impaired users, at least to those, who use screen readers. They are also frequently recommended by previous works such as e.g. by Kim et al. [KJRK21] or Sharif et al. [SCWR21].

In the study conducted for this thesis, the textual descriptions of the visualizations proved divisive. One participant stated that these were their favorite feature and that they wished, every visualization would have such descriptions. They even stated they would like it if the description was a little longer and more detailed. In contrast, another participant stated, that they would like for the detailed descriptions to be completely removed and replaced by a simple title that only states the type and topic of the visualization without giving any description of the elements, statistics, or trends. This participant stated that they prefer access to the raw data and that to them the description was too interpretative. This confirms the results of a study by Siu et al. [SFK<sup>+</sup>21] that found that many blind and visually impaired users are skeptical of description texts since they force them to rely on someone else's interpretation of the data and since they are often out-of-date, meaning the visualization has been updated, but the description has not been adapted to reflect the changes. Since the descriptions were very useful to one participant and considered harmful by another one, it is difficult to resolve this and give a definitive conclusion here. Some researchers such as Sharif et al. [SCWR21] have recommended automatically generating image descriptions from the underlying data to make sure that they are accurate and up-to-date. If doing this became the norm in the industry, this might help with trust in visualization descriptions. However, it does not help if it is done on one individual website, since for the user there is no way of knowing that the description was generated based on current data. This also does not fully resolve the issue with interpretative descriptions, since automatically generated descriptions can be biased, too. Sharif et al. [SCWR21] also suggested that the generated description text should be personalized for each user according to their preferences. This might solve the problem by providing a very short description to users who are skeptical of descriptions. However, there are no suggestions, on how this kind of personalization could be implemented in practice, so this is something that would need to be explored in future works.

## 7.5 Need for semantics and structure

Sensibly structuring a website and writing the markup using semantic HTML allows screen reader users to efficiently and confidently navigate the resulting website. For instance, when headings are properly marked up as headings, screen reader users can use keyboard shortcuts to access a list of headings and to quickly jump between headings. Headings are well-established elements on websites. There are the HTML heading elements <h1> to <h6> for different levels of headings and it is generally understood what the semantics of a heading element are. For the domain of data visualization this luxury often does not exist. There is no pre-existing element for marking up data points, tooltips or axes. This makes it harder to implement these elements so that they can be efficiently navigated and so that their semantics are adequately communicated to screen reader users. This difficulty presented itself during development and was confirmed in the evaluation study. For instance, when making the data points in the line chart screen reader accessible, it was not clear, how to mark the year, the births value and the deaths value in the tooltip of one data point as belonging together and being one unit.

This issue was then confirmed in the study, where it happened, that a participant got confused about which value belongs to which year, since they did not know in which order they appear in the tooltip. This kind of confusion is probably to blame for participants occasionally choosing the previous or following, incorrect value instead of the correct one, when working on the tasks. More research would be needed to develop techniques and best practices for expressing semantics and properly marking up typical visualization elements so that the elements, their boundaries and their semantics are communicated to screen reader users.

Better semantics and structure are needed not just for a better understanding of the elements of the visualization, but also to enable more efficient navigation. Some participants were observed skim-reading the description texts, the data points or the table with their screen reader. To do this they would always listen shortly and then skip a bit and then listen again. However, since the data points in the visualization and the image description were not structured in a way that allowed efficient navigation using a screen reader, the participants were always missing more or less random pieces of information when they were skipping ahead. This resulted in multiple instances of a participant listening to the textual descriptions while solving a task, skipping over the part of the description that would have contained the answer and then moving on to use a different feature to solve the task. This might be prevented by structuring the long text better into segments. Using HTML markup to better structure textual descriptions is also something that has been previously suggested by Kim et al. [KJRK21], but that was not implemented in the prototype. One participant also suggested using markup to make it easier to jump between data points using a keyboard shortcut. They suggested to make e.g. the year a heading, so that they could use the keyboard shortcut for jumping from heading to heading for quickly navigating between data points. Something similar has been suggested before by Siu et al. [SFK<sup>+</sup>21], however no concrete guidance was given yet as to how this might be implemented. The same participant also suggested to shorten the tooltip content for more efficient navigation. Similarly another participant suggested to shorten the column headers, since they are read out by the screen reader many times while navigating the table. Further research should examine, how screen reader users can be enabled to skim-read and efficiently navigate within visualizations and their related features. However, especially when shortening or omitting content in tooltips or table headings, special care needs to be taken, as not to worsen the cognitive accessibility of the visualization.

In the study it also became apparent that some fully blind screen reader users did not know that they were navigating through the data points inside the visualization. One participant was asked about what they thought which part of the website they were currently on, when they were going through the data points in the visualization. They replied that they thought they were in a list below the actual visualization. This can also partly be attributed to the fact, that there was no adequate way of marking this part up as being inside the actual visualization. While this is not a critical usability issue, it could make it more difficult for a blind user to communicate with a sighted person about the website, since they would have different ideas of the structure and the parts of

the visualization. Further research might examine how to create data visualizations that allow blind users to form a similar mental map of the page as sighted users.

## 7.6 Sonification needs a clear concept

The data sonification was not useful to the participants yet and every participant offered some criticism and suggestions for improvement with regards to this feature. This was expected, as this was the most experimental feature of the prototype and as it was primarily included to spark discussion with the participants.

Multiple participants experienced a lack of orientation while the sonification played and stated that they were missing a frame of reference. They expressed trouble knowing where they currently are in the sonification, e.g. to which year the current sound belongs. But they also had trouble distinguishing the pitch and understanding which sounds were especially high- or low-pitched and thus represented especially high or low data values. One participant was so confused by the sonification that they needed to be given an extra explanation, so that they would understand what they are hearing. Kim et al. [KJRK21] have previously pointed out the issue that mappings can be unclear in sonifications.

The question that this issue raises is what the concept and purpose of a data sonification should be. The varying feedback of the participants showed that they had quite differing visions for how this feature might become useful. One participant imagined the sonification as something to gain a fast impression of the data. They suggested to speed up the sonification and use one continuous sound that changes over time instead of playing one sound for each data point. Other participants seemed to have a different concept in mind, where the sonification would allow more detailed access to the data. They requested that there would be an announcement of the current year or age group and that sample sounds would be provided that demonstrate a high, a medium and a low value to provide a frame of reference. One participant with usable residual vision also noted that they would prefer, if the sonification was connected to the visualization. They suggested allowing users to play individual values e.g. by clicking on the data points in the visualization. Despite giving suggestions about improving the sonification, two participants were doubting, whether the sonification might ever become useful to them.

These results show that a clearer concept is needed when including a data sonification. Depending on whether the sonification is meant to e.g. give a short overview of the data or to access and compare individual data points, very different implementations would be needed. More research is needed on which concepts would provide the most value to users and how they would need to be executed in practice to become useful.

## 7.7 Recommendations need to be practical

Implementing the prototype for this work was difficult for many reasons. But the biggest issue was the lack of guidance with regards to the details of the implementation. The idea of the synthesized guidelines (see chapter 4) was to provide recommendations that help visualization creators with developing visualizations that are more accessible. This

list was purposefully written in the form of recommendations and not in the form of testing criteria such as e.g. Chartability [Ela22], since testing criteria are not always helpful with how something needs to be implemented, so that it will meet the criteria. Since the synthesized recommendations were partly based on testing criteria catalogues [Ela22, AMTGS21], the recommendations suffered from similar issues of not providing enough guidance on how to put them into practice. For instance, one recommendation is to include a textual description of the data visualization. But there is little guidance on how to best do this. This guidance, however, would be necessary, since a complex data visualization will usually not be an image with an `alt` attribute for a textual description, which would be the standard way of doing this. Since there is a lack of research in this area, not much practical guidance could be found and included in the synthesized recommendations. Therefore, the actual implementation of the visualization and the accessibility features was largely based on experimentation, experience and continuous testing of the accessibility. This approach was, however, very time-consuming and would be hard to reproduce. Another issue in this regard was also, that the resulting features would not consistently work across different browser and screen reader combinations. Sometimes access of the individual data points in the prototype would behave differently when using different screen readers. Sometimes bugs would occur, where the screen reader read numbers incorrectly. Achieving a result that worked consistently across the spectrum of devices, browsers and assistive technologies, was not completely possible. Therefore, more research is needed in this regard. Research and industry need to develop best practices and recommendations for the implementation of accessible data visualizations that enable developers to create consistently accessible visualizations without needing to spend extensive efforts experimenting and innovating.

# Conclusion

The goal of this work was to add to the knowledge in the field of visualization accessibility. Since visualizations frequently occur on websites in the form of dashboards, statistics and charts, the focus was set on the accessibility of data visualizations on websites, that are implemented using common web technologies. Since blind and visually impaired persons frequently encounter barriers with data visualizations, the focus of this work was on accessibility for this target group. This thesis confirmed many results of previous works, showing that the field is moving into the right direction with its recommendations. At the same time, new insights were also gained. This chapter highlights the key contributions of this thesis and lays out the limitations of the work as well as possible areas for future research.

## 8.1 Key contributions

The work done in this thesis was split into three parts: A synthesis of recommendations for accessible data visualization, the development of a prototype based on the recommendations, and the evaluation of the prototype with blind or visually impaired persons. This thesis provides three key contributions which result from these three parts of the work.

**Contribution 1: Synthesized recommendations** Even though visualization accessibility is a field that only recently started gaining more research interest, some researchers have already given recommendations about what to consider when creating accessible data visualizations. These existing recommendations have been synthesized into a list of 19 recommendations that can be followed to create web-based data visualizations that are accessible to blind and visually impaired persons. These could be used by visualization creators to create more accessible visualizations. They could also be refined and built upon by future works.

**Contribution 2: Prototype** The synthesized guidelines were used to create a prototype in the form of a website. The website contains two data visualizations that have been developed according to the synthesized recommendations. This prototype demonstrates one way of translating the recommendations into practice. Since the recommendations are not always straightforward to translate into design and code, the prototype can serve as an artifact that visualization creators can take inspiration from, when they are developing their own visualizations. Researchers could also explore further ways to create accessible visualization and compare the accessibility of the resulting prototypes.

**Contribution 3: Insights from the study** A formative evaluation of the prototype was conducted with five blind or visually impaired participants. Its results showed that the prototype was generally very usable to the target group and that following the recommendations resulted in mostly accessible visualizations. This provides the insight that current recommendations in the field of visualization accessibility actually work in making visualizations accessible. Furthermore, the observations and interview answers from the study provided further insight into various aspects of visualization accessibility. The study confirmed the importance of providing multiple ways of accessing a visualization e.g. by providing not just a textual description, but by also offering a data table. The findings also drew attention to the importance of making data tables interactive, since sorting and filtering can be crucial features for solving some tasks. The results further showed that some parts of visualization accessibility can be hard to get right since the preferences of users sometimes go in opposite directions. It was found that there are users who love detailed textual descriptions of visualizations, while there are others, who would like to have them shortened to the bare minimum.

### 8.2 Limitations

While the contributions of this work provide a valuable addition to the knowledge in this field, they are limited in a few ways, which are discussed below.

**Number of study participants** One limitation of this work lies in the number and characteristics of the study participants. The prototype was evaluated with five participants who had varying levels of blindness or severe visual impairment. Through the diversity in vision levels, very interesting insights could be gained in the prototype evaluation, since the participants varied a lot in preferences and in how they interacted with the prototype. However, since there were only five participants in total, the observed preferences and interactions can't be directly generalized to entire groups of people with a specific level of blindness or visual impairment. Some of these observations might be just due to personal preference or other reasons. Further studies are needed to better understand the needs and preferences of users with diverse types and degrees of visual impairment.



**Choice of visualizations** The contributions of this work are also limited in the choice of visualizations that were included in the prototype. Since the field of visualization accessibility is still researching the base for visualization accessibility, very common, basic visualizations were chosen: a bar chart and a line chart. The visualizations were also kept simple and not very interactive. This was done on purpose, as to explore ways for how web-based visualizations can be made accessible at all. This, however, limits the applicability of the findings to basic visualizations. Further research would be needed to see how more complex, innovative and highly interactive visualizations can be made accessible to blind or visually impaired persons.

**One researcher doing everything** The fact that all steps in this work were carried out by the same person limits the results in one way. The same person first authored the recommendations and then applied them during the development of the prototype. If a different developer was given the list of recommendations, it might have been harder for them to build a accessible visualizations according to them. But since I, as the author of this thesis and the recommendations also developed the prototype, I might have unknowingly applied additional knowledge that I gained from previous research, but that was not made explicit in the recommendations. It was tried to reduce the impact of this limitation by following the written recommendations closely without consulting other works during development. But more research with other developers would be needed to see, whether they, too, could use the recommendations to build accessible visualizations.

**Choice and presentation of data** Lastly, one limitation was found in the choice and presentation of the data set. The data presented in the prototype was demographic data from Germany. In order to prevent study participants from drawing on prior knowledge about the demographics of Germany, the data was presented in the prototype as belonging to the fictional country “Loremland”. One participant, however, quoted prior knowledge when asked about how they solved a task. They claimed, that this data would be similar for countries around the world and that they, thus, could use their prior knowledge to solve the task. Even though other participants did not make similar claims, it can’t be guaranteed, that other participants were not also partly drawing on supposed prior knowledge that coincidentally might have helped them and might have made it easier for them to comprehend the presented data and solve the tasks. For future evaluations it is recommended to choose the data and it’s presentations carefully to prevent similar effects.

## 8.3 Future work

Visualization accessibility is a field that presents many opportunities for future research. Lots of possible areas of futures research have already briefly been pointed out throughout chapter 7, as well as in section 8.2 of this chapter. These are the key recommendations for focus areas of future research seeking to build on this work:

**Diversity in visual impairment and preferences** The evaluation of the prototype showed that preferences and ways of interacting with the visualizations often differed strongly between participants. This could be in part explained due to their different levels of visual impairment. Future works should improve the understanding of the diverse preferences and ways of interacting with visualizations for people across the spectrum of visual impairment and blindness. Especially the group of users who are severely visually impaired and use a screen reader, but who still extensively leverage their residual vision should not be forgotten.

**Textual description needs** Two study participants had directly opposing opinions about the textual descriptions of the visualizations. One of them wanted them to be reduced to a bare minimum, while the other one liked the level of detail and would have liked if they had been even more extensive. The dislike of the description by the one participant was partly based on distrust towards the description. Further research should seek to better understand the diverse needs of blind or visually impaired persons with regards to descriptions of visualizations.

**Accessibility of complex visualizations** The prototype created for this work included a line chart and a bar chart, since it's important to establish the foundation of how common types of visualizations can be made accessible. However, often data visualizations on the internet can take more novel, more complex and more interactive forms. Future research should explore how well the given recommendations can be applied to these more complex visualizations, what barriers blind and visually impaired persons face when interacting with them and how they can be made accessible.

# List of Figures

3.1	The prototype when Windows' built-in high contrast mode is active (in Firefox). . . . .	19
5.1	The start page of the prototype which links to the visualization pages . . .	36
5.2	The main page of the line chart visualization . . . . .	38
5.3	The bar chart visualizing the distribution of the population into age groups	39
5.4	The line chart visualizing the number of births and deaths per year. . . .	40
5.5	The colors chosen for the line chart in a color vision deficiency simulator [Nic]	41
5.6	The line chart with a tooltip that reads out "Year: 1993", "Births: 798.447", "Deaths: 897.270". . . . .	44
5.7	The fullscreen view of the bar chart in a strongly zoomed-in state. The buttons are labeled (from left to right) "zoom out", "zoom in", "reset" and "close".	49
5.8	The table for the line chart with three columns "year", "births" and "deaths".	51
5.9	The sonification feature of the line chart. At the top a text explains how to use the feature. Below the user can choose which data to listen to and press play or pause. . . . .	54



Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar  
The approved original version of this thesis is available in print at TU Wien Bibliothek.

# List of Tables

4.1	The works that have been included in the synthesis of the recommendations.	28
6.1	Correct and incorrect answers with and without answer options given by task.	58



Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar  
The approved original version of this thesis is available in print at TU Wien Bibliothek.

# List of Listings

1	The CSS code for a system font stack which allows the browser to pick a font that is already commonly used on the user’s device. . . . .	42
2	The CSS code for hiding an element visually, but keeping it accessible for screen readers. Implemented as suggested by Coyier in [Coy19]. . . . .	45
3	The wrapping div of the visualizations with the “role” and “aria-label” attributes that improve discoverability for screen reader users. “Diagramm” is German for “diagram”. . . . .	46
4	The screen reader accessible implementation of a chart axis. Translation of the axis description text: “X-axis, shows age, split into twenty age groups starting with 0–4 and ending with 95–99.” . . . . .	47
5	The screen reader accessible implementation of the bars in the bar chart. . . . .	48
6	The function for updating the zoom level of the fullscreen view. . . . .	50
7	The base HTML of one of the tables. . . . .	52
8	The TypeScript code that generates the table entries. . . . .	52
9	The implementation of the CSV download. . . . .	53
10	The CSV file from the bar chart “population_by_age.csv”. . . . .	53
11	The code that creates the scale for mapping values to pitch. . . . .	54
12	The code that creates the tone sequence for the sonification. . . . .	56



Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar  
The approved original version of this thesis is available in print at TU Wien Bibliothek.



# Bibliography

- [AMTGS21] Rubén Alcaraz Martínez, Mireia Ribera Turró, and Toni Granollers Saltiveri. Methodology for heuristic evaluation of the accessibility of statistical charts for people with low vision and color vision deficiency. *Universal Access in the Information Society*, 21:863–894, May 2021. doi:[10.1007/s10209-021-00816-0](https://doi.org/10.1007/s10209-021-00816-0).
- [Ass] American Optometric Association. Low Vision and Vision Rehabilitation. Accessed: 2022-05-26. URL: <https://www.aoa.org/healthy-eyes/caring-for-your-eyes/low-vision-and-vision-rehab?sso=y>.
- [BM13] Matthew Brehmer and Tamara Munzner. A Multi-Level Typology of Abstract Visualization Tasks. *IEEE Transactions on Visualization and Computer Graphics*, 19(12):2376–2385, December 2013. Conference Name: IEEE Transactions on Visualization and Computer Graphics. doi:[10.1109/TVCG.2013.124](https://doi.org/10.1109/TVCG.2013.124).
- [Bos] Mike Bostock. D3.js - Data-Driven Documents. Accessed: 2023-04-03. URL: <https://d3js.org/>.
- [BSB] Ofer Bartal, Mohammad Suliman, and Eilana Benish. Accessible Graphs. Accessed: 2022-04-21. URL: <https://accessiblegraphs.org/>.
- [CJP<sup>+</sup>19] Jinho Choi, Sanghun Jung, Deok Gun Park, Jaegul Choo, and Niklas Elmqvist. Visualizing for the Non-Visual: Enabling the Visually Impaired to Use Visualization. *Computer Graphics Forum*, 38(3):249–260, 2019. Number: 3. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1111/cgf.13686>, doi:[10.1111/cgf.13686](https://doi.org/10.1111/cgf.13686).
- [Coy19] Chris Coyier. Inclusively Hidden, April 2019. Accessed: 2023-04-07. URL: <https://css-tricks.com/inclusively-hidden/>.
- [CSFB06] Sambhavi Chandrashekar, Tony Stockman, Deborah Fels, and Rachel Benedyk. Using think aloud protocol with blind users: a case for inclusive usability evaluation methods. In *Proceedings of the 8th international ACM SIGACCESS conference on Computers and accessibility*, Assets '06, pages

251–252, New York, NY, USA, October 2006. Association for Computing Machinery. doi:10.1145/1168987.1169040.

- [Desa] Statistisches Bundesamt Destatis. Bevölkerungspyramide: Altersstruktur Deutschlands von 1950 - 2060. Accessed: 2023-04-03. URL: <https://service.destatis.de/bevoelkerungspyramide/index.html#!y=2018>.
- [Desb] Statistisches Bundesamt Destatis. Federal Statistical Office of Germany. Accessed: 2023-04-03. URL: [https://www.destatis.de/EN/Home/\\_node.html](https://www.destatis.de/EN/Home/_node.html).
- [Des23a] Statistisches Bundesamt Destatis. 12612-0001: Lebendgeborene: Deutschland, Jahre, Geschlecht, April 2023. Accessed: 2023-04-03. URL: <https://www-genesis.destatis.de/genesis/online?operation=table&code=12612-0001#astructure>.
- [Des23b] Statistisches Bundesamt Destatis. 12613-0002: Gestorbene: Deutschland, Jahre, Geschlecht, April 2023. Accessed: 2023-04-03. URL: <https://www-genesis.destatis.de/genesis/online?operation=previous&levelindex=0&step=0&titel=Tabellenaufbau&levelid=1680521482201&acceptscookies=false#astructure>.
- [EBM22] Frank Elavsky, Cynthia Bennett, and Dominik Moritz. How accessible is my visualization? Evaluating visualization accessibility with Chartability. *Computer Graphics Forum*, 41(3):57–70, 2022.
- [Ela21] Frank Elavsky. Chartability, November 2021. Accessed: 2021-11-18. URL: <https://chartability.fizz.studio/>.
- [Ela22] Frank Elavsky. The Chartability Workbook, 2022. Accessed: 2022-09-07. URL: <https://chartability.github.io/POUR-CAF/>.
- [Elm23] Niklas Elmquist. Visualization for the Blind. *Interactions*, 30(1):52–56, January 2023. doi:10.1145/3571737.
- [EMW19] Christin Engel, Emma Franziska Müller, and Gerhard Weber. SVGPlott: an accessible tool to generate highly adaptable, accessible audio-tactile charts for and from blind and visually impaired people. In *Proceedings of the 12th ACM International Conference on PErvasive Technologies Related to Assistive Environments*, PETRA '19, pages 186–195, New York, NY, USA, June 2019. Association for Computing Machinery. doi:10.1145/3316782.3316793.
- [FIT] Föderale IT-Kooperation FITKO. Data licence Germany – attribution – version 2.0. Accessed: 2023-04-03. URL: <https://www.govdata.de/dl-de/by-2-0>.

- [Fou23] The OpenJS Foundation. ESLint - Pluggable JavaScript Linter, March 2023. Accessed: 2023-04-03. URL: <https://eslint.org/>.
- [IfDRa] Policy & Practice Institute for Disability Research. WAVE Web Accessibility Evaluation Tools. Accessed: 2023-04-03. URL: <https://wave.webaim.org/>.
- [IfDRb] Policy & Practice Institute for Disability Research. WebAIM: Contrast Checker. Accessed: 2023-04-03. URL: <https://webaim.org/resources/contrastchecker/>.
- [IfDRc] Policy & Practice Institute for Disability Research. WebAIM: Survey of Users with Low Vision #2 Results. Accessed: 2023-04-03. URL: <https://webaim.org/projects/lowvisionsurvey2/>.
- [JRG<sup>+</sup>22] Shakila Cherise S Joyner, Amalia Riegelhuth, Kathleen Garrity, Ye-Seul Kim, and Nam Wook Kim. Visualization Accessibility in the Wild: Challenges Faced by Visualization Designers. In *CHI Conference on Human Factors in Computing Systems*, CHI '22, pages 1–19, New York, NY, USA, April 2022. Association for Computing Machinery. doi:10.1145/3491102.3517630.
- [KJRK21] N. W. Kim, S. C. Joyner, A. Riegelhuth, and Y. Kim. Accessible Visualization: Design Space, Opportunities, and Challenges. *Computer Graphics Forum*, 40(3):173–188, 2021. \_eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/cgf.14298>. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1111/cgf.14298>, doi:10.1111/cgf.14298.
- [KLL<sup>+</sup>22] Shankar Kantharaj, Rixie Tiffany Ko Leong, Xiang Lin, Ahmed Masry, Megh Thakkar, Enamul Hoque, and Shafiq Joty. Chart-to-Text: A Large-Scale Benchmark for Chart Summarization. *arXiv:2203.06486 [cs]*, April 2022. arXiv: 2203.06486. URL: <http://arxiv.org/abs/2203.06486>.
- [LAKM07] Jonathan Lazar, Aaron Allen, Jason Kleinman, and Chris Malarkey. What Frustrates Screen Reader Users on the Web: A Study of 100 Blind Users. *International Journal of Human-Computer Interaction*, 22(3):247–269, May 2007. Publisher: Taylor & Francis \_eprint: <https://doi.org/10.1080/10447310709336964>. doi:10.1080/10447310709336964.
- [LCI<sup>+</sup>20] Bongshin Lee, Eun Kyoung Choe, Petra Isenberg, Kim Marriott, and John Stasko. Reaching Broader Audiences With Data Visualization. *IEEE Computer Graphics and Applications*, 40(2):82–90, March 2020. Number: 2. doi:10.1109/MCG.2020.2968244.

- [LS22] Alan Lundgard and Arvind Satyanarayan. Accessible Visualization via Natural Language Descriptions: A Four-Level Model of Semantic Content. *IEEE Transactions on Visualization and Computer Graphics*, 28(1):1073–1083, January 2022. doi:10.1109/TVCG.2021.3114770.
- [MLB<sup>+</sup>21] Kim Marriott, Bongshin Lee, Matthew Butler, Ed Cutrell, Kirsten Ellis, Cagatay Goncu, Marti Hearst, Kathleen McCoy, and Danielle Albers Szafr. Inclusive data visualization for people with disabilities: a call to action. *Interactions*, 28(3):47–51, April 2021. Number: 3. doi:10.1145/3457875.
- [Nic] David Nichols. Coloring for Colorblindness. URL: <http://www.davidmathlogic.com/colorblind/>.
- [Pro] The GNOME Project. Projects/Orca - GNOME Wiki! Accessed: 2023-04-03. URL: <https://wiki.gnome.org/Projects/Orca>.
- [SCWR21] Ather Sharif, Sanjana Shivani Chintalapati, Jacob O. Wobbrock, and Katharina Reinecke. Understanding Screen-Reader User’s Experiences with Online Data Visualizations. In *The 23rd International ACM SIGACCESS Conference on Computers and Accessibility, ASSETS ’21*, pages 1–16, New York, NY, USA, October 2021. Association for Computing Machinery. doi:10.1145/3441852.3471202.
- [SF18] Ather Sharif and Babak Forouraghi. evoGraphs — A jQuery plugin to create web accessible graphs. In *2018 15th IEEE Annual Consumer Communications Networking Conference (CCNC)*, pages 1–4, Las Vegas, NV, USA, January 2018. ISSN: 2331-9860. doi:10.1109/CCNC.2018.8319239.
- [SFK<sup>+</sup>21] Alexa F. Siu, Danyang Fan, Gene S-H Kim, Hrishikesh V. Rao, Xavier Vazquez, Sile O’Modhrain, and Sean Follmer. COVID-19 highlights the issues facing blind and visually impaired people in accessing data on the web. In *Proceedings of the 18th International Web for All Conference, W4A ’21*, pages 1–15, New York, NY, USA, April 2021. Association for Computing Machinery. doi:10.1145/3430263.3452432.
- [SHZA16] Sarit Felicia Anais Szpiro, Shafeka Hashash, Yuhang Zhao, and Shiri Azenkot. How People with Low Vision Access Computing Devices: Understanding Challenges and Opportunities. In *Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility, ASSETS ’16*, pages 171–180, New York, NY, USA, October 2016. Association for Computing Machinery. doi:10.1145/2982142.2982168.
- [SMTC20] Irena Serna-Marjanović, Anel Tanovic, and Ajla Cerimagic. Accessibility Standards and Their Implementation in Custom Data-Driven Maps. In *2020 43rd International Convention on Information, Communication and Electronic Technology (MIPRO)*, pages 1674–1679, Opatija, Croatia, September 2020. ISSN: 2623-8764. doi:10.23919/MIPRO48935.2020.9245417.

- [Str21a] Adam Strantz. Beyond “Alt-Text” Creating Accessible Data Visualizations with Code. In *The 39th ACM International Conference on Design of Communication*, SIGDOC ’21, pages 331–337, New York, NY, USA, October 2021. Association for Computing Machinery. doi:10.1145/3472714.3473661.
- [Str21b] Adam Strantz. Using Web Standards to Design Accessible Data Visualizations in Professional Communication. *IEEE Transactions on Professional Communication*, 64(3):288–301, September 2021. Number: 3. doi:10.1109/TPC.2021.3091784.
- [SWM<sup>+</sup>22] Ather Sharif, Olivia H. Wang, Alida T. Muongchan, Katharina Reinecke, and Jacob O. Wobbrock. VoxLens: Making Online Data Visualizations Accessible with an Interactive JavaScript Plug-In. In *CHI Conference on Human Factors in Computing Systems*, CHI ’22, pages 1–19, New York, NY, USA, April 2022. Association for Computing Machinery. doi:10.1145/3491102.3517431.
- [W3C21] World Wide Web Consortium W3C. Web Content Accessibility Guidelines (WCAG) 2.1, November 2021. Accessed: 2021-11-18. URL: <https://www.w3.org/TR/WCAG21/>.
- [W3C23] World Wide Web Consortium W3C. Web Accessibility Laws & Policies, April 2023. Accessed: 2023-04-29. URL: <https://www.w3.org/WAI/policies/>.
- [WHO22] World Health Organization WHO. ICD-11 for Mortality and Morbidity Statistics. Version 2022-02, 2022. Accessed: 2022-05-26. URL: <https://icd.who.int/browse11/l-m/en#/http%3a%2f%2fid.who.int%2ficd%2fentity%2f1103667651>.
- [WOH<sup>+</sup>15] Markus Weninger, Gerald Ortner, Tobias Hahn, Olaf Drümmer, and Klaus Miesenberger. ASVG - Accessible Scalable Vector Graphics: intention trees to make charts more accessible and usable. *Journal of Assistive Technologies*, 9(4):239–246, January 2015. Publisher: Emerald Group Publishing Limited. doi:10.1108/JAT-10-2015-0027.
- [WPA<sup>+</sup>21] Keke Wu, Emma Petersen, Tahmina Ahmad, David Burlinson, Shea Tanis, and Danielle Albers Szafir. Understanding Data Accessibility for People with Intellectual and Developmental Disabilities. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pages 1–16, New York, NY, USA, May 2021. Association for Computing Machinery. URL: <https://doi.org/10.1145/3411764.3445743>.
- [WTS19] Keke Wu, Shea Tanis, and Danielle Szafir. Designing Communicative Visualization for People with Intellectual Developmental Disabilities. Tech-

nical report, OSF Preprints, August 2019. type: article. URL: <https://osf.io/zbjhr/>, doi:10.31219/osf.io/zbjhr.

# Appendix

## A.1 Session protocol

This is the checklist that was used to conduct the study sessions step-by-step.

### Introduction

1. Start audio call (no camera).
2. Welcome participant, explain the study and procedure: First consent, then base data, then tasks and then the interview.
3. Send them the voucher.
4. Verify that they signed the consent form. Ask if there are any questions about it. If they haven't signed it, do oral consent:
  - Start recording.
  - Say date.
  - Ask them to say their name.
  - Ask if they read the consent form, understood it.
  - Read out point 1 to 5 and ask, whether they consent to every one of them. Consent to number 5 is optional.
  - Stop recording.
5. Tell them that they can stop or pause the study any time. Tell them, that not they are being tested, but that it is the prototype that is being tested.
6. Ask if they have questions before we start. Tell them that they can ask questions anytime, but that I might not be able to answer every question.
7. Ask about base participant data and enter it into a spreadsheet.

## Tasks

1. Ask participant, whether they are ready for the tasks.
2. Ask participant, whether they had a chance to look at the prototype already before the study. If they didn't: Ask the participant to familiarize themselves with the visualization (5 min).
3. Ask for permission to start recording.
4. Start recording the meeting.
5. Ask participant to share their screen with audio.
6. Send the participant the link to the visualizations. Ask them to open it and to maximize the window, so that the visualization is visible in the screen sharing transmission.
7. Ask the participant if they are ready to for the tasks.
8. Tell participant that they can have the task reread anytime. Ask them to give the answers to the tasks verbally.
9. Tell them, that if needed they can receive three answer options to choose from for each task.
10. Pose one task after the other, reading it out loud. The answer options will read out loud (if applicable). Don't correct them if their answer is wrong.
11. Ask them, after each task, how they solved it.

## Interview

1. Conduct a structured interview about their experience with the visualizations and the tasks. Follow the interview guide.

## Ending

1. End the recording.
2. Thank them for their participation.
3. Ask them whether they have any questions or anything they would like to discuss outside of the study now.
4. End the call.
5. Save the recording and verify, that it is intact.



## A.2 Base participant data

This is the base data that was recorded for each participant at the start of the session.

- Age
- Gender
- Are they confident in doing daily use activities with the device they participated with?
- Short description of their visual disability.
- Currently working or used to work with web accessibility?
- Currently work or used to work with diagrams?
- Operating system of the device they are on.
- Web browser they will use in the study.
- If applicable, screen reader they will use in the study.
- If applicable, other assistive technology they will use during the study.

## A.3 Tasks (German original)

These are the tasks as they were posed to the participants during the prototype study.

### Tasks for the bar chart displaying the age groups.

**Wie viele Leute sind in der Altersgruppe 40 bis 44 Jahre?** Ask this first without giving the answers.

- 5,583,000 (wrong, following age group)
- 4,841,000 (correct)
- 5,236,000 (wrong, previous age group)

Wie sind Sie da drauf gekommen?

**Was ist die Altersgruppe mit der größten Anzahl an Leuten?** Ask this first without giving the answers.

- 50 - 54 (correct)
- 55 - 50 (wrong)
- 60 - 64 (wrong)

Wie sind Sie da drauf gekommen?

### Wie lassen sich die Daten im Altersbereich 10 bis 34 Jahre beschreiben?

- Grundsätzlich ist die Anzahl der Menschen pro Gruppe in diesem Bereich sehr ähnlich. (wrong)
- Je älter die Gruppe ist, desto größer ist sie. Am größten ist die Gruppe 30-bis-34-Jahre. (correct)
- Je älter die Gruppe ist, desto kleiner ist sie. Am größten ist die Gruppe 10-bis-14-Jahre. (wrong)

Wie sind Sie da drauf gekommen?

### Tasks for the line chart displaying the number of births and deaths

**Wie groß ist die Anzahl der Geburten im Jahr 2003?** Try this without giving them the answers first.

- 719,250 (wrong, 2002 value)
- 705,622 (wrong, 2004 value)
- 706,721 (correct)

Wie sind Sie da drauf gekommen?

### In welchem Jahr ist die Anzahl der Geburten am größten?

- 1964 (correct)
- 2021 (wrong)
- 1990 (wrong)

Wie sind Sie da drauf gekommen?

**In welchem Jahr ist die Anzahl der Sterbefälle zum ersten Mal größer als die Anzahl der Geburten?** Try this without giving them the answers first.

- 1972 (correct)
- 1988 (wrong)
- 1971 (wrong)

Wie sind Sie da drauf gekommen?

## Wie verläuft die Zahl der Geburten zwischen 1997 und 2011

- Die Zahl der Geburten fällt leicht. (correct)
- Die Zahl der Geburten steigt leicht. (wrong)
- Die Zahl der Geburten schwankt etwas, aber ist im Grunde stabil. (wrong)

Wie sind Sie da drauf gekommen?

## A.4 Interview questions (German original)

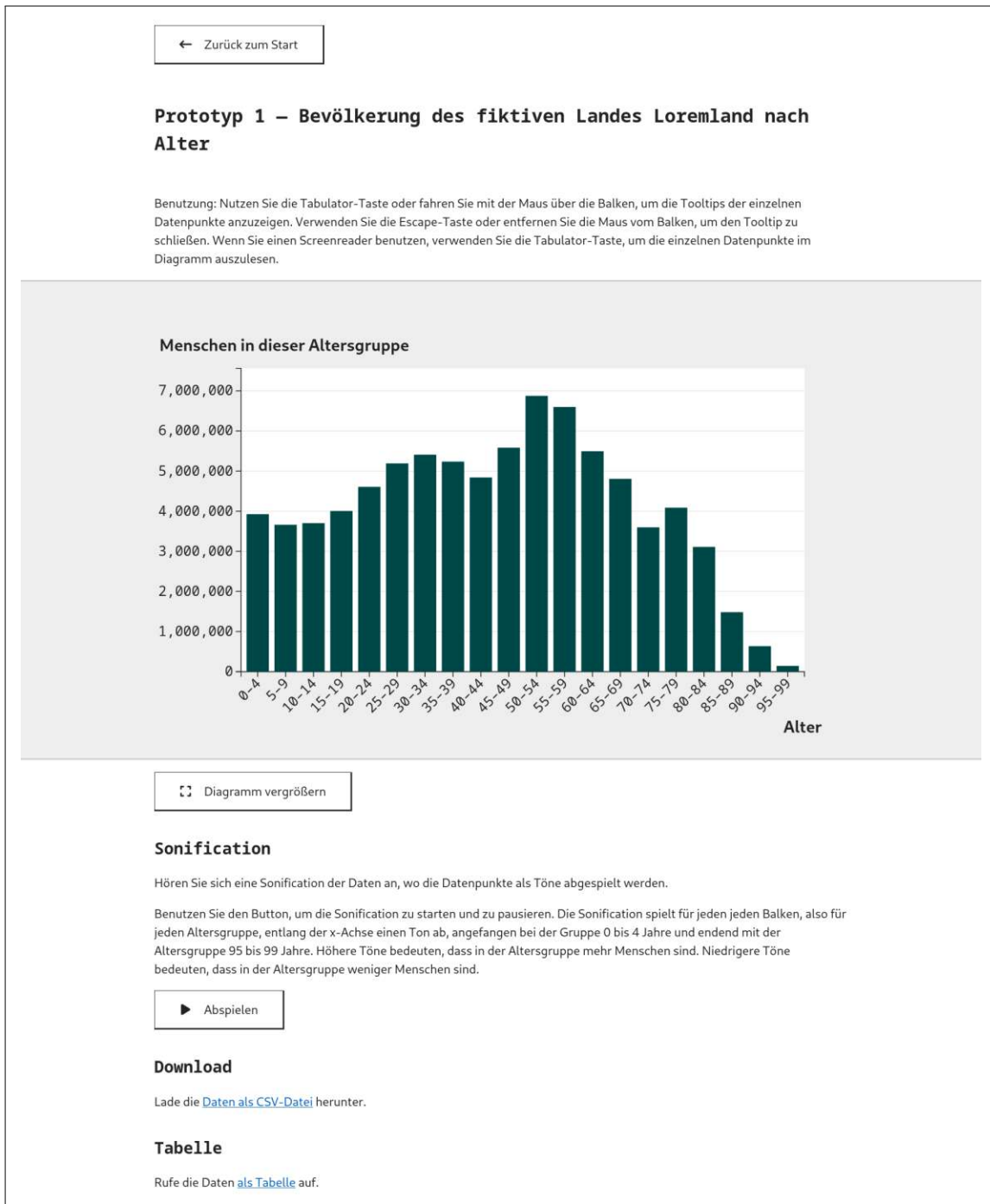
1. Waren die hier präsentierten Diagramme für Sie besser, schlechter oder ähnlich gut benutzbar im Vergleich zu anderen Diagrammen, die Sie sonst auf Webseiten antreffen?
2. Welche Features der Diagramme waren besonders nützlich? Welche Teile des Prototyps haben Ihnen besonders gefallen? Warum?
3. Welche Features der Diagramme waren nicht nützlich, nicht verständlich oder nicht gut zu benutzen? Welche Teile des Prototyps haben Ihnen nicht gefallen? Warum?
4. Gab es irgendwas an diesen Diagrammen, das für Sie neu oder überraschend war?
5. Hat Ihnen irgendwas gefehlt? Gibt es noch etwas das Sie sich gewünscht hätten, damit die Diagramme besser zu benutzen wären?
6. Was halten Sie von der Sonification? War sie nützlich? Könnten Sie sich vorstellen, dass so etwas bei Diagrammen auf echten Webseiten einen Nutzen hätte?
7. Wenn Sie ein Feature des Prototyps aussuchen könnten, dass in Zukunft die Diagramme auf anderen Webseiten dann auch hätten, welches wäre das?
8. Gibt es noch etwas, das Sie gerne sagen würden?

## A.5 Interview questions (English translation)

1. In general, would you say the usability of these diagrams was better, worse of similar for you, compared to other diagrams you encounter on websites?
2. Which features of the diagrams were especially useful to you? Which parts of the prototype did you especially like? And for which reasons?
3. Which features of the diagrams were not useful, not understandable or not easily usable? Which parts of the prototype did you not like and for what reasons?
4. Was there anything new or surprising about the diagrams?

5. Is there anything you were missing? Is there anything you would have wished for, so that the diagrams would be more usable.
6. What are your thoughts on the sonification? Was it useful? Could you imagine that something like this would be useful in diagrams on actual websites?
7. If you could pick one feature of this prototype that would then become available in the future in the diagrams on other websites, what would you choose?
8. Is there anything else you would like to say?

## A.6 Further screenshots



The main page of the bar chart visualization