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R. Borgo, G. E. Marai, and T. Schreck
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How accessible is my visualization? Evaluating visualization accessibility with Chartability

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Abstract

Novices and experts have struggled to evaluate the accessibility of data visualizations because there are no common shared guidelines across environments, platforms, and contexts in which data visualizations are authored. Between non-specific standards bodies like WCAG, emerging research, and guidelines from specific communities of practice, it is hard to organize knowledge for how to evaluate accessible data visualizations. We present Chartability, a set of heuristics synthesized from these various sources which enables designers, developers, researchers, and auditors to evaluate data-driven visualizations and interfaces for visual, motor, vestibular, neurological, and cognitive accessibility concerns. In this paper, we outline our process of making a set of heuristics and accessibility principles for Chartability and highlight key features in the auditing process. Working with participants on real projects, we find that data practitioners with a novice level of accessibility skills are more confident and find auditing to be easier after using Chartability. Expert accessibility practitioners are eager to integrate Chartability into their own work. We reflect on the tradeoffs of open projects, working with high-risk evaluations like auditing projects in the wild, and challenge future research projects at the intersection of visualization and accessibility to consider the broad intersections of disabilities in addition to and beyond vision.

CCS Concepts

• Human-centered computing* → *Visualization design and evaluation methods; Accessibility design and evaluation methods; Heuristic evaluations;

1. Introduction

26% of people in the United States self-report living with at least one disability [CDC19]. Of those, 13.7% live with a mobility disability and 10.8% with a cognitive disability. Globally, the World Health Organization reports that 29% of the world lives with uncorrected or uncorrectable blindness, low vision, or moderate to severe visual impairment [Org]. Access is a significant inclusion effort that has broad international impact, especially for data visualization.

Accessibility is the practice of making information, content, and functionality fully available to and usable by people with disabilities. As part of this process, practitioners need to be able to identify accessibility barriers. Fortunately, there are accessibility standards and inclusive design principles which guide such auditing and the design of documents, tools, websites, and software to be more accessible. But while these general standards help, evaluating the inaccessibility of complex data systems can be a daunting and often expensive task. For example, state-of-the art automated compliance checkers only find 57% of accessibility errors [noa21c] meaning accessible experiences must still be manually designed and checked for quality, requiring a non-trivial investment of time. Additionally, the intended wide applicability of these general standards means they fall short for information-rich systems. Examples might include guiding content creators in how to prioritize content to reduce cognitive labor, developing techniques to reduce manual and tedious tasks when performing statistical analysis, and enabling users to customize a data-driven experience to suit their personal needs. Further, standards lack guidance for many of the specific challenges raised by data visualizations (which use size, color, angles, shapes, and other dimensions to encode information). Specific contexts, communities, and libraries that deal with data visualizations and information-rich interfaces often have their own tools and guidelines for use. Research at the intersection of data visualization and accessibility tends to deal with concerns that are specific in scope, largely biased towards vision-specific disabilities.

Synthesizing evolving accessibility standards, research findings, and artifacts from communities of practice into usable knowledge for a specific domain of work that is also evolving is a wicked problem. To address this problem, we present Chartability. Chartability is an accessibility evaluation system specific to data visualizations and interfaces which aims to help practitioners answer the question, "how accessible is my data visualization?" Chartability organizes knowledge from disparate bodies of work into testable heuristics based on the functional accessibility principles POUR (Perceivable, Operable, Understandable, and Robust) [IW] with 3 additional principles CAF (Compromising, Assistive, and Flexible) added to attend to the unique qualities and demands of data visualizations. We refer to these 7 heuristic principles as POUR+CAF.

Chartability is a community-contributed project that leverages open involvement as a way to address the complex dual-evolution of both accessibility and data interaction practices.

We additionally present an initial, light evaluation of Chartability from the experience of practitioners using it. We set out to see if using Chartability reduces the barrier of entry into this work for accessibility novices and if accessibility experts had any feedback to share about its use. We gave practitioners introductory material for Chartability and instructed them to use it according to their needs. We found that before using Chartability only accessibility experts believed auditing data visualizations to be somewhat easy or easy, while the other group believed auditing data visualizations to be somewhat hard or hard. All novice accessibility practitioners became more confident after using Chartability and believed auditing data visualizations for accessibility to be less difficult. Conversely while the expert accessibility practitioners were already confident in their ability to evaluate accessibility (and all unanimously had no change in their before and after evaluations), they were excited to adopt Chartability into their set of auditing resources.

Our work sets out to acknowledge that data practitioners face significant barriers when first making data visualizations, systems, and experiences accessible. While Chartability contributes to filling gaps and organizing knowledge, it also challenges visualization and data interaction researchers to explore new horizons of possibilities in this space. As such, we conclude with recommendations for future research at the crossroads of data visualization and accessibility.

2. Existing Work in Data Visualization and Accessibility

While recent works at the intersection of data visualization and accessibility are promising, they do not provide a consistent and unified methodology for designers to evaluate the accessibility of their work across the broad spectrum of disability considerations.

2.1. Research Advancements in Data Visualization and Accessibility

In parallel to Mack et al.'s "What do we mean by Accessibility Research?" [MMJ*21] when we asked "What do we mean by data visualization accessibility research?" we found that nearly all topics of study were vision-related. Largely, access issues other than vision that affect data visualization (such as cognitive/neurological, vestibular, and motor concerns) are almost entirely unserved in this research space. Kim et al. found that 56 papers have been published between 1999 and 2020 that focus on vision-related accessibility (not including color vision deficiency), with only 3 being published at a visualization venue (and only recently since 2018) [KJRK21]. Marriot et al. found that there is no research at all that engages motor accessibility [MLB*21]. We have found 3 papers that engage cognitive/neurological disability in visualization, which are all recent (specifically intellectual developmental disabilities [WPA*21] and seizure risk [SB20, SSB21]). We found no papers that engage vestibular accessibility, such as motion and animation-related accessibility. We also found that there is no research specific to low vision disabilities (not blindness or color vision deficiency) unless conflated with screen reader usage in data visualization. Blind and low vision people are often researched together, but in practice may use different assistive technologies (such as magnifiers and contrast enhancers) and have different interaction practices (such as a combination of sight, magnification, and screen reader use).

Since the 1990s, the most prominent and active accessibility topic in visualization has been color vision deficiency [CC17, NAR18, Oli13, LCI*20, MTS21]. Despite this, accessibility research on charts and graphs for the blind that explore tactile sensory substitutions have been a topic in computational sciences dating back to the 1983 [GSF83], with tactile sensory substitutions being used for maps and charts as far back as the 1830s [noa16]. Sonification used both in comparison to and alongside visualization and tactile methods for accessibility dates as far back as 1985 [MBJ85, FBT97, Bre02, MB06, ZPSL08, CM19]. Some more recent work has evaluated screen reader user experiences with digital, 2-D spatial representations, including data visualizations [SHW21, SCWR21], dug deeper into the semantic layers of effective chart descriptions [LS22], and explored how to better understand the role that sensory substitution can play [CPR*22]. Jung et al. offer guidance that expands beyond commonly cited literature that chart descriptions are preferably between 2 and 8 sentences long, written in plain language, and with consideration for the order of information and navigation [JMK*22]. We find all of this emerging work promising and foundational.

Despite promising work emerging, Lundgard et al. laid theoretical and methodological considerations warning against the dangers of "disability dongles" and technosolutionist approaches [LLS19]. Disability design expert Liz Jackson calls disability dongles: a "well intended, elegant, yet useless solution to a problem we [people with disabilities] never knew we had" [Jac19]. Considering this critical lens, we also want to highlight that research at the intersection of data visualization and accessibility is not all generalizable or applicable to the goal of our project because it has practical limits. There is significant research that exists that explores automatic or extracted textual descriptions [CJP*19, BRS18, CZK*19, CZK*20, LLJ*20, OH20, QKD*21, SF18] and haptic graphs and tactile interfaces [Ald08, BPW15, BH12, BHR*21, GS11, GSF83, JDI*15, JRW*07, LTJ86, Sch, SZFA16]. Many of these research projects are high-cost for individual use, some are not robust enough to produce or interpret complex visualizations effectively, and several projects have not included people with disabilities at all. Many of these projects did not follow existing accessibility standards in the research process and results, such as using Web Content Accessibility Guidelines [noas], The American Printing House for the Blind and Braille Authority of North America [noaf], or the work of Gardiner and Perkins [noao]. All of these are factors that limit the generalizeability of these artifacts and knowledge for practitioner use [BJJ*10, LLS19, MSMC14, MJBC18, SCWR21].

2.2. Accessibility Practices in Data Visualization Tools and Libraries

Our research goals are to find what is already being done in data visualization and accessibility and to see if we can enhance that activity. To this aim, it is important to include sources that may be an archival risk, such as web blogs, articles, guides, and even Github repositories.

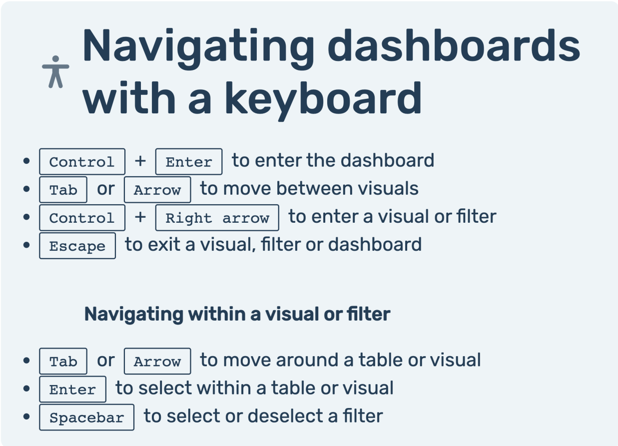


Figure 1: *Keyboard instructions provided for a PowerBI dashboard, built by the City of San Francisco. PowerBI provides the functionality but does not provide instructions during the use of dashboard operation. These had to be built by developers.*

Libraries like Highcharts [noaa] or Visa Chart Components (VCC) [noap] and tools like the Graphics Accelerator in SAS [noam] have broad accessibility functionality built in, but their documentation is technically specific to their implementation. While these relatively accessible libraries and tools can be helpful for inspiration, their non-generalizable techniques and guidance materials are not easily transferrable to other environments or applications where data visualizations are created. Practitioners must reverse engineer and deconstruct many of the methods employed by these libraries, and with the exception of VCC (which is open source), this task requires significant effort.

Accessibility engineering is often not present, limited in scope, or has only recently become an effort in common charting tools and libraries (apart from those already mentioned). More established visualization libraries like matplotlib, ggplot2, d3js, R-Shiny, and Plotly have left most accessibility efforts to developers, with varying levels of documentation and difficulty involved [noa18a, noa18b, Hon20, noal, noa19, sim20]. None of these major tools have a broad spectrum of accessibility options built in and documented.

Community contributors often must fight to make their tools and environments accessible (sometimes even against the design of the tools themselves) with little to no compensation for their contributions. For example, Tableau's first accessible data table was built by a volunteer community member Toan Hong as an extension [Hoa18]. Tableau users more broadly must resort to voting systems to gather attention to accessibility issues [DeM]. Semiotic's accessibility features were added by community member Melanie Mazanec [noan]. For Microsoft's PowerBI, students have organized resources for how to make visualizations built with it more accessible [noak] while non-profits like the City of San Francisco's data team have had to build features like keyboard instructions from scratch (see Figure 1) [noab]. Mapbox GL JS is an example of a popular mapping library (over 400,000 weekly downloads) [noai] that has no built-in accessibility support by default. The accessibility module for Mapbox GL on GitHub was created and maintained by volunteers but has had less than 10 weeks of work with any activity invested since its first activity in late 2017 [noa21b].

Many community-driven efforts are under-utilized, must be discovered outside of the primary environment's ecosystem, have poor or no core, internal support, and are inconsistently and partially implemented. Accessibility is still an afterthought in data visualization and ad-hoc, specific solutions proposed have not led to widespread improvements.

2.3. Accessibility in Practice, Broadly

Accessibility in practice is largely motivated by standards work or assistive technology. We want to acknowledge that tactile and braille standards are robust [noaf, noao], but have limited transferability to digital contexts currently. For example, whereas tactile graphics guidelines lend insight into information prioritization, layout, and fidelity, the assumption is they will be embossed onto paper or similar physical mediums [BJJ*10, LLS19, SCWR21].

In digital contexts, the most influential body for accessibility is the World Wide Web Consortium's (W3C) Web Accessibility Initiative (WAI). WAI's Web Content Accessibility Guidelines (WCAG) [noas] influence accessible technology policy and law for more than 55% of the world's population [IW21]. WAI and WCAG outline 4 types of functional accessibility principles: Perceivable, Operable, Understandable, and Robust, abbreviated as POUR [IW]. POUR is the foundation that organizes all 78 accessibility testing criteria in WCAG.

2.4. Using Heuristics to Break Into Under-addressed Areas

So our problem space is complex: Research in data visualization primarily focuses on visual accessibility, accessibility standards focus on a broad range of disabilities but lack deep contextualization for data visualization, and practitioners seem to build a wide array of solutions to fill these gaps, most of which are poorly maintained or adopted.

Any time that a practitioner wants to embark on a journey learning how to evaluate the accessibility of a data visualization, they must collect and synthesize this complex space of knowledge themselves. We received permission to include an exemplary field artifact as an example of this type of labor from Adrian Feldman of the United States Government's 10x project, "Improving Accessibility in Data Visualizations" [noag, noac]. We have archived the data from their survey with their permission and included it in our supplementary materials.

We decided to leverage the advantages of heuristic evaluation models as a space to optimistically construct a useful artifact. Heuristic evaluation models have a long history in HCI and are cheap to use and require little expertise. They have been shown to be effective methods for practitioners compared to user testing, focus groups, or other evaluative methods that require existing expert knowledge or recruitment, moderation, and compensation of participants [MTS21, CSA15, BUSC18, Exp, JLBJ16, Nie94, Ote17, SSD18, SC99, noa18c]. Heuristics are also not new in visualization [FJ10, CC05, OS22, Sch11] even among topics related to accessibility (color vision deficiency, specifically) [SSD18, Oli13].

3. Making Chartability

Before discussing our process making Chartability, it should be known that it does not neatly fit into most design models that divide researchers from practitioners. In Gray's different models of practitioner-researcher relations, our work is some iteration of *bubble-up, practitioner-led* research [GSS14]. This project was initiated by the primary author while they were an industry practitioner, deeply situated in this work already. We appropriated certain methods like using coding from grounded theory in our making or likert scale questions alongside open interviews in our validating.

With that narrative in mind, we believe that our method of making is still valuable to document and contribute to the larger research community. Chartability was created over the course of 10 months using the following process:

1. **Situate, survey, and select**: We were situated within the context of accessibility evaluations of data visualizations and recognized the prohibitively significant labor involved in ensuring we were effective in our own work. In order to improve this work both for ourselves and others, we surveyed existing problems and challenges others faced and selected a solution that we felt equipped to address.
2. **Evaluate and collect**: We set out to answer: If evaluating the accessibility of data experiences is hard, what do existing standards miss? We evaluated our seed knowledge (WCAG criteria) for shortcomings and gaps and collected other data relevant to our goal (research and practitioner artifacts).
3. **Code (categories and themes)**: We loosely borrowed from thematic analysis [BC06] and qualitatively coded all our data according to WCAG's POUR principles (including testing if WCAG criteria fit neatly into only one principle) as well as 25 additional categories. We then analyzed and organized our categorized data into themes.
4. **Synthesize**: We synthesized our themes into 45 heuristics, combining them with testing procedures and tools from auditing. We also tagged which heuristics were still backed by standards and if not, which at least had peer-reviewed research. 8 heuristics remained (out of 45) that are still largely driven by practitioner work, addressing gaps in standards and research. Our supplemental materials include the data from this stage of our process, but you can see a preview in Table 1.
5. **Theorize**: 26 heuristics fit neatly back into Perceivable, Operable, Understandable, or Robust while 19 heuristics with complex themes and overlapping categories demanded new theorizing. We grouped these complex themes into 3 new principles, Compromising, Assistive, and Flexible.

3.1. Theorizing 3 New Accessibility Principles Beyond POUR

In our work coding categories and themes across our data, we immediately recognized that even WCAG criteria had fairly complex category overlaps. Only 12 of WCAG 2.1's 78 criteria fit neatly into a single principle (Perceivable, Operable, Understandable, or Robust). Most criteria straddled two of WCAG's Principles, typically with one as a primary.

Table 1: *Previewing Chartability's 10 Critical Heuristics*

			Coding Categories	
Heuristic	Principle	Type	POUR	Other
Low contrast	Perceivable	Standard	P	2
Small text	Perceivable	Research	P	2
Only visual	Perceivable	Standard	P, R	3
Output has only one Input	Operable	Standard	O, R	3
No interaction cues/instructions	Operable	Standard	O, U	2
No explanation for how to read	Understandable	Research	U	1
No title, summary, or caption	Understandable	Research	U	1
No table	Compromising	Research	O, U, R	3
Data density inappropriate	Assistive	Research	P, U	4
User style change not respected	Flexible	Standard	P, O, R	6
... +35 non-Critical heuristics				

The messy space we created by categorizing our data with these 4 principles demanded that we also categorize our data again before analyzing groupings and patterns. We coded 25 additional categories for our data, which allowed us to confidently group 26 of our heuristics under POUR (each averaging 1.5 POUR principles and 1.8 additional categories each). Of the remaining 19 heuristics, 13 of them involved Robust. We considered these heuristics much more complex (averaging 2.5 POUR principles and 3.8 additional categories each).

Among these 19 complex heuristics, we found 3 strong groups emerge:

1. **Compromising** (Understandable, yet Robust): based on providing alternative, transparent, tolerant, information flows with consideration for different ways that users with assistive technologies will prefer to consume different information.
2. **Assistive** (Understandable and Perceivable but labor-reducing): included categories that encourage data interfaces to be intelligent and multi-sensory in a way that reduces the cognitive and functional labor required for their use.
3. **Flexible** (Perceivable and Operable, yet Robust): focused on respecting user settings from user agents (browsers, operating systems, applications) and providing presentation and operation control.

As a final step, we organized all of our 19 remaining heuristics under these 3 new principles. We preview an example of how we organized and documented our heuristics in Table 1: Previewing Chartability's 10 Critical Heuristics. We also discuss what led to our special categorization of "critical" in subsection 5.2.

3.1.1. Compromising

Compromising is a principle that challenges designs that only allow access to information through limited or few interfaces or processes. People with disabilities consume information in many different ways. Compromising heuristics focus on providing information at a low and high level (such as tables and summaries), transparency about the state of complex interactions, and the requirement that data structures can be navigated in more than just a serial fashion.

Compromising also has heuristics that are sorely underdiscussed in accessibility, even in communities of practice, how to create understandable history, saving, undoing, branching analysis, and linking functionalities. One heuristic (related to state sharing) in this category was explicitly synthesized out of studying artifacts, as opposed to written articles. We use the robust URL-sharing capabilities in Google Maps [noad] as an exemplary artifact of this type of design, even though enterprise data applications, dashboards, and products rarely design and develop this capability.

3.1.2. Assistive

Assistive is a principle that requires data experiences to reduce the cognitive and functional labor required of the user as much as possible. This means that charts and graphs should be designed to handle extreme values, high density, complex statistics, and present more than just visual summaries but also narrative, auditory, or tactile summaries as well.

The Assistive principle focuses on what Pickering et al. refer to as “adding value” [noah] and what Doug Schepers meant by “data visualization is an assistive technology” [noat]. We visualize because it is faster and more efficient than munging cell at a time through data. Assistive heuristics ensure that this efficient experience is accessible for people with disabilities.

3.1.3. Flexible

Contrasted with Compromising (which focuses on robust understanding), flexible heuristics focus on robust user agency. The flexible principle had the most consistent grouping of categories, all heuristics shared at least the 4 categories “flexible,” “user-controlled,” “respectful,” and “empowering.”

Flexible heuristics all have a tight coupling between a data experience and the larger technological context the user inhabits. The presentation and operation preferences that a user sets in lower level systems must be respected in higher level environments.

Self-advocacy and interdependent agency are important sociotechnical considerations that engage the conflicting access needs that different users might have in complex technological interactions like data experiences [BBB18, MHK10]. Some users might want specific controls or presentation, while others might want something else entirely. Designs must not be *rigid* in their opinions and ability assumptions and should be designed to be moldable by and adaptive to user needs [WKG*11, Lad15].

4. Using Chartability

All of Chartability’s tests are performed using Chartability’s workbook [REMOVED FOR ANONYMOUS SUBMISSION] alongside various tools and software (linked in the workbook). For the scope of this paper, we are not including an explanation for how to perform all of these. Both the workbook and supplementary materials with this paper give more details.

While a highly trained auditor may be able to casually evaluate an artifact in as little as 30 minutes or even hold heuristics in

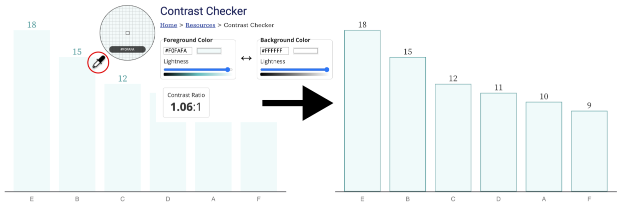


Figure 2: *A low contrast chart (left) compared to a higher contrast version (right). A dropper tool is extracting the fill color of the bar and then a contrast ratio has been calculated. Note that the fill color is the same on both bars, but darker borders have been added to ensure the visualization passes contrast tests.*

mind as they are doing their own creative work, those new to auditing may take anywhere between 2 and 8 hours to complete a full pass of Chartability. Professional audits, which can take weeks or months, often include multiple auditors and provide rigorous documentation and detailed recommendations for remediation, typically in the form of a report. Chartability is meant to serve both quick pass and deep dive styles of audits, so users are expected to leverage it as they see fit.

Below we give an example of what might be a quick pass audit, using Chartability.

4.1. Visual Testing

Checking for contrast is the most common critical failure across all of our audits (88% of audits failed this heuristic). In order to evaluate contrast, often a combination of automatic (code-driven) and manual tooling is performed. When manually auditing, practitioners typically use a dropper and a contrast calculator (Figure 2). Contrast is measured by finding adjacent colors that are intended to convey meaning or boundaries, and finding a ratio between them. Standards require a different minimum contrast for text (4.5:1) than geometries like marks in a chart (3:1). Most auditors find this to be one of the easiest tasks to perform, but techniques can be tricky to handle. Testing for contrast accomplishes 3 different heuristics in Chartability: ensuring text/geometries have contrast, interactive states for elements have enough contrast change, and the keyboard focus indicator is easy to distinguish.

Perceivable heuristics also include tests and tools for color vision deficiency and ensuring that color alone isn’t used to communicate meaning (like the redundantly encoded textures in Figure 9). And another common, critical failure from Perceivable is text size. No text should be smaller than 12px/9pt in size.

4.2. Keyboard Probing

The next practice that most auditors should become comfortable with is using a keyboard to navigate and operate any functionality that is provided. Most assistive technologies, from screen readers to a variety of input devices (like switches, joysticks, sip and puffs, etc) use the keyboard api (or keyboard interface) to navigate content. If a data interface contains interactive elements (Figure 3, Figure 4), those elements (or their functionality) must be able to be

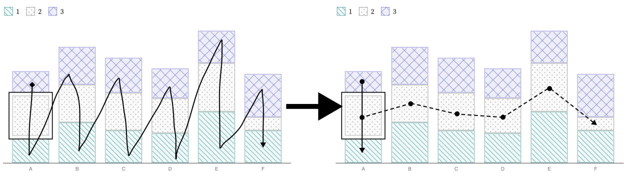


Figure 3: *Keyboard navigation paths on a stacked bar chart. The left shows a serial navigation example, typically just a default of rendering order. The right shows both groups (the stack of bars) and categories (the color/texture shared among bars across stacks) as dimensions to explore laterally or vertically.*

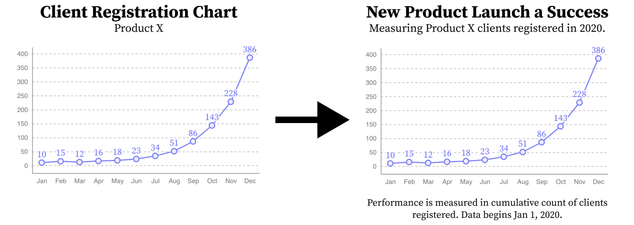


Figure 5: *Charts must have a visually available textual explanation provided that summarizes the outcome. "Client Registration Chart" for "Product X" (left) is inaccessible while "New Product Launch a Success" (right) gives a clear takeaway.*

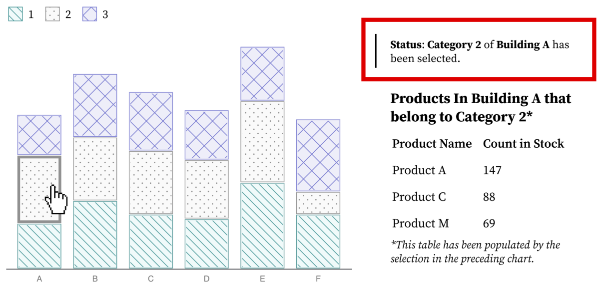


Figure 4: *A mouse cursor is selecting a bar (left, shown with a thick indication border) in a stacked bar chart to filter a dataset (on the right). A system alert (red box) notifies the user of their interaction result. This selection capability must also be provided for the keyboard interface and the alert must be announced to screen readers.*

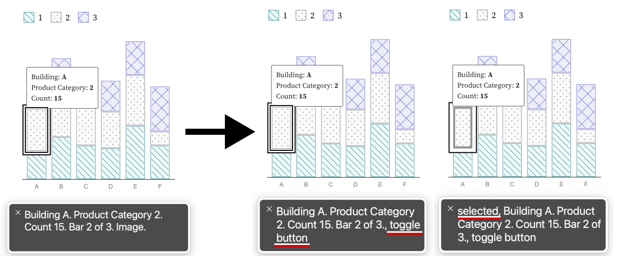


Figure 6: *An interactive chart displaying only "Image" as semantic information with no feedback provided on selection. The robust semantics given to a screen reader, "toggle button" (middle) as well instant feedback, "selected" (right) are considered proper semantics for an interactive experience.*

reached and controlled using a keyboard alone. Auditors should be critical of how much work is involved in keyboard navigation, especially (Figure 8). All that is required to start is the auditor begins pressing the tab key to see if anything interactive comes into focus. Arrow keys, spacebar, enter, and escape may be used in some contexts. Generally, instructions or cues should always be provided.

Using a keyboard provides an opportunity to evaluate many different heuristics: checking for multiple inputs (Figure 4), whether the data structure that is rendered is navigable according to its structure (Figure 3), and whether keyboard navigability across all elements in a data interface is even necessary (Figure 8).

4.3. Screen Reader Inspecting

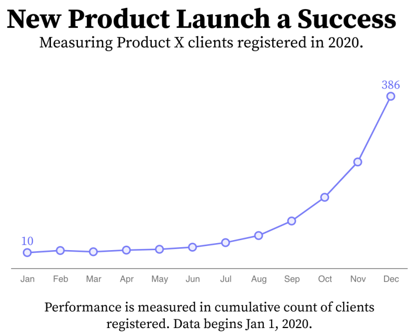
Closely related to keyboard testing is testing with a screen reader. Some things may work with a screen reader that do not with a keyboard (and vice versa), so both must be evaluated.

Screen readers, unlike more basic keyboard input devices, read out content that is textual (including non-visual textual information like *alternative text*). Using a screen reader to audit is generally the hardest skill to learn. Keeping this in mind, testing whether the meaningful text provided in a visual (such as in Figure 5) is accessible with a screen reader is the easiest and most basic test that auditors should first perform.

Next, all valuable information and functionality in a data experience should tested whether it is available to a screen reader. This includes the individual variables about a mark as well as whether that mark is interactive (Figure 6), whether status updates that reflect context change provide alerts (Figure 4), and whether summary textual information is provided about the whole chart (Figure 5) as well as statistically and visually important areas of that chart (Figure 8).

4.4. Checking Cognitive Barriers

First, auditing for cognitive barriers generally involves checking the reading level and clarity of all available text using analytical tools. But Chartability also requires that all charts have basic text provided that provides a visually-available textual description and takeaway (Figure 5). This alone is one of the most important things to check for. In complex cases where a chart has a visual feature with an assumedly obvious takeaway, checking for annotations or textual callouts is important to help avoid interpretive issues [XVWF20] (Figure 8).



Month	Registered Clients
Jan	10
Feb	15
Mar	12
Apr	16
May	18
Jun	23
Jul	34
Aug	51
Sept	86
Oct	143
Nov	228
Dec	386

Figure 7: *A line chart (left) with a single line and an accompanying data table (right). This line chart would not provide enough low-level information about each datapoint without the table provided. A table alone however would also be inaccessible. Providing both can satisfy conflicting accessibility needs for different audiences.*

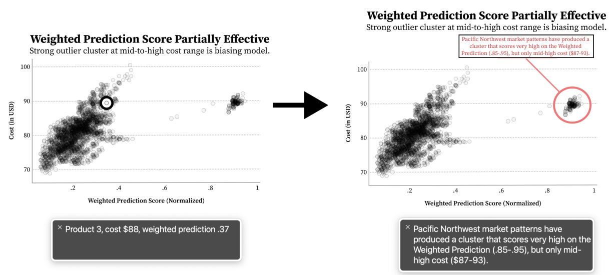


Figure 8: *A scatterplot with many points, where a single point within the chart can be accessed by a screen reader (left). Navigating this data piece by piece is unnecessarily tedious, so an annotation callout is provided to help the reader focus on an outlier cluster (right). The callout is being accessed by a screen reader, which is displaying the annotation's summary as well.*

4.5. Evaluating Context

The final series of checks an auditor should make involve thinking about the overall work in a design (as it intersects with other considerations) as well as the larger technical context where the user is situated.

Auditors should first try to change system settings (such as toggling high contrast modes) to see whether a data experience respects these settings (Figure 9), run automatic semantic evaluations as well as manually check for appropriate meaning (Figure 6), and check if dense or highly complex visuals have sonified, tactile, or textual summaries available (Figure 8). Auditors should also check whether system updates provide clear feedback textually (Figure 4) as well as checking if there are both high and low level representations of information available (Figure 7).

Auditors should be especially critical of static designs, such as those that either use textures by default or not (Figure 9), which are a high risk of compromising and adaptive failure.

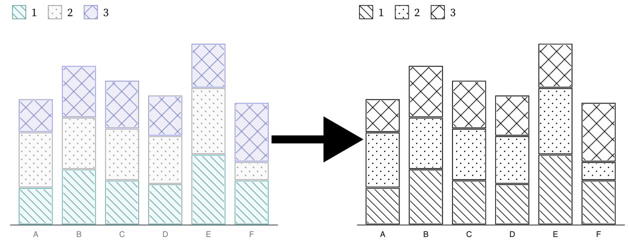


Figure 9: *A bar chart with categories (left) shown not conforming to Windows High Contrast White Mode. High contrast mode on Windows requires limiting color palettes, using only black or white for most elements (shown on the right).*

5. Validating Chartability

Our primary goal was to reduce the prohibitive barrier of entry in this line of work. We set out to validate whether data practitioners felt more confident and equipped to make their own work accessible with Chartability. Additionally, we also wanted to interview expert accessibility practitioners (including those with disabilities) with the same questions, to see if Chartability had anything to offer in helping them understand and evaluate data experiences better.

Our secondary goal was to present a tool that can be helpful even in the wild on real projects (with all the weird design and engineering quirks that come with that). We wanted Chartability to be usable on things built with a tool like Tableau and fully bespoke, hand-coded visualizations, like those made with JavaScript and D3. To this secondary aim, we intentionally solicited participants who were working on a variety of different projects, each of their own design.

5.1. Pre-Validations and Flipped Roles: Participants Question Us

We actually performed several early, light validations of our work before soliciting and involving participants formally. Our early pre-validations #2-4 (below) all focused on practitioners asking us questions and giving us feedback.

Our 4 pre-validations happened during the process of making, as well as introducing short iterations back into the making process:

1. **Beta Testing**: We performed several beta tests of Chartability during the process of making. This was important to determine early on if it had potential to keep developing.
2. **Early Advice**: We sent Chartability via email to 4 accessibility experts and 6 interested people with disabilities familiar with auditing in order to solicit open feedback.
3. **Professional Workshop**: We held a half-day professional workshop via zoom on auditing visualizations for accessibility and presented our heuristics to this select audience of 50 participants. We demonstrated how to audit and then had a chance for feedback and questions.
4. **Deep Feedback Session**: We presented Chartability to 14 experts on data visualization and accessibility, 5 of which are people with disabilities. We presented in two separate sessions

through two hour video calls on zoom (roughly one hour demonstration and one hour for discussion).

5.2. Discovering "Critical" Heuristics

Our pre-validations helped us combine and divide some of our heuristics, adjust our language and phrasing, and also label 10 specific tests as "Critical," which can be seen in Table 1. These critical tests were ones that community members stressed as an important priority for one or more of the following reasons:

- They are prohibitively expensive to fix late.
- The barriers they produce are too significant to ignore.
- They are among the most common type of accessibility failure.
- They affect many parts of a data experience.

All Critical heuristics are based on standards or research.

5.3. Selecting Participants and Projects

The primary author was a practitioner and representing themselves as a volunteer when we reached out to participants. At this stage in the project, we were still not affiliated with a research institution and were not interested in producing publishable, generalizable knowledge. We intended to test Chartability in the wild and validate whether it achieved its aims. Our priority was to collaborate with folks working on difficult problems or those who had a rare intersection of expertise between accessibility standards and interactive data experiences. To this end, we were highly permissive with our potential collaborators in order to maximize the expertise of participants and breadth of environments for testing Chartability.

However, part of being permissive with participants meant that we were willing to collaborate on projects that we cannot share in a research publication and many of our participants must remain anonymous (including interview results that contain sensitive information about intellectual property). Given that auditing is a field of work about identifying failures, there was both a high demand for participation in our evaluation of Chartability and a low motivation to make these failures known in a public venue. We want to caution researchers who are considering evaluating their work in similar environments to consider the tradeoffs between evaluation in rich, authentic professional settings and concerns such as intellectual property and corporate branding.

A summary of our selection process:

- **Solicitation**: We reached out via email to 24 individuals in our network to participate in helping us evaluate Chartability. We mentioned that we wanted Chartability to be applied to a current project of theirs and were interested in performing some interviews about their experience before and after using Chartability. We mentioned up front that working with us would be uncompensated and potentially take multiple hours of their time (even multiple sessions) over zoom meetings.
- **Response**: 16 individuals were interested and shared their project details (2 would require an NDA to be signed).
- **Selection**: We selected 8, based either on the expertise of the individuals, on the robustness of their project, and/or on the opportunity to get feedback about Chartability in team environments (which we didn't anticipate, but 3 of the 8 represented team efforts).
- **Resulting Group**: We worked with 19 total participants across 8 environment spaces.
- **Publishable Group**: Due to intellectual property concerns, we can publish interview results from 6 participants and discuss the details of 4 audit environments.

Chris DeMartini: a multi-year Tableau Zen Master and recognized expert visualization practitioner. His dashboard of a coin flipping probability game dataset that he produced with his daughter was the subject of his audit [noar]. His audit only included criteria labelled Critical in Chartability (which involves only 10 tests instead of the full 45) and his dashboard failed 7 of them. A full audit was later conducted on Chris' behalf. His full audit had a total 26 failures, 11 of which were considered non-applicable.†

Amber Thomas: a data storyteller and technologist credited on 30 of The Pudding's visual essays. Amber has had a growing interest in accessibility challenges related to her line of work designing and developing state of the art, bespoke visual essays. Her article The Naked Truth was still in the early design and development stages when it was fully audited [noaj]. It failed 22 out of 45 tests, including 6 out of 10 criteria considered Critical. 6 tests were considered non-applicable.†

Sam (self-selected name): a recognized design practitioner in the visualization community who lives with disability. They were collaborating on an interactive data project that would be specifically made to be used by international participants with a broad spectrum of disabilities. Their interactive infographic failed 21 out of 45 tests, 5 of which were considered Critical. 10 tests were considered non-applicable.†

Øystein Moseng: Core Developer and Head of Accessibility of Highcharts. Øystein was interested in taking one of Highchart's demo charts not specifically developed with accessibility features in mind [noae] and testing it against a full Chartability audit to see how it held up. The demo failed 13 out of 45 tests, 3 of which were Critical. 10 tests were considered non-applicable.†

Jennifer Zhang: a senior accessibility program manager at Microsoft with expertise working on enterprise data products.

Ryan Shugart: a blind, screen reader user and disability subject matter expert at Microsoft who has a strong expertise in collaborative accessibility for interactive data systems.

Both Shugart and Zhang were interested in applying Chartability internally and testing its effectiveness and potential with various projects. Their application and use of Chartability (including audits) are not available for publication, but their valuable interviews and evaluations are included with permission.

† "Non-applicable:" any test in the auditing process that that does not contain content relevant to the test, such as "Scrolling experiences cannot be adjusted or opted out of" for a visualization that does not a scrolling input control

6. Study Results

We asked the 6 participants a series of qualitative and Likert-scale evaluation questions:

1. Have you ever performed an audit of a data experience before?
2. What stage of production is your project in? Analysis, design, prototyping, development, maintenance?
3. How confident are you in your ability to perform an audit of a data experience for accessibility issues? (1-5, 1 being not confident at all, 5 being fully confident.)
4. How difficult do you perceive auditing a data experience for accessibility issues is? (1-5, 1 being trivial, 5 being very difficult.)
5. (After using Chartability) How confident are you in your ability to perform an audit of a data experience for accessibility issues? (1-5, 1 being not confident at all, 5 being fully confident.)
6. (After using Chartability) How difficult do you perceive auditing a data experience for accessibility issues is? (1-5, 1 being trivial, 5 being very difficult.)
7. (After using Chartability) Do you intend to continue using Chartability?

Each of these questions had an open-ended question attached, "Is there anything else you would like to add?" Every participant provided additional input on questions 3 through 7.

None of the 3 participants who only consider themselves expert data practitioners had performed an audit before. All 3 of them reported that they believed auditing to be easier and that they are more confident in their ability to evaluate the accessibility of data experiences after using Chartability.

Of the 3 accessibility experts (all of whom have performed audits of data experiences before), their opinions on these measurements were unchanged after using Chartability. All six participants noted that they plan to use Chartability in their own work and would recommend it to their peers.

6.1. Real Access has more Considerations than Colorblindness

Among the data practitioners, DeMartini wrote after his audit, "I have read a lot about color blindness and could provide meaningful feedback to visualization developers on that topic, but I have come to realize that accessibility is so much more than this and I basically didn't really know where to start when it came to the true scope of accessibility." He ended his qualitative feedback with, "I think this could be a great tool for the masses and really look forward to the impact it can possibly have on the (inaccessible) data visualizations which are being created in huge numbers these days."

6.2. Audits are Slow, but Help me Focus

Amber Thomas wrote, "It still takes a while to do a complete audit, but it's not hard! For someone new to the space, all the possible options that can be used to make visualizations more accessible can be overwhelming. [Chartability] helped me to focus." She finished her feedback with, "There aren't really guidelines (at least to my knowledge) that exist to help data visualization creators to ensure their work is accessible... [Chartability] helps to direct users to the most common accessibility problems with straightforward questions. It really helps to narrow the focus and prioritize efforts."

6.3. Chartability Helps me Remember and Stay Consistent

Among the accessibility experts, Zhang wrote, "While I am skilled, depending on the day I might not remember everything I need to look at. I am more confident in consistency between different auditing sessions. For experts it's a good reminder framework." Moseng of Highcharts noted, "[Chartability] did a very good job of highlighting concerns that are often ignored or forgotten when auditing and designing/developing." Shugart of Microsoft added along those lines, "I feel [Chartability] arranges a good set of questions in a user's mind and makes it easier for them to determine if a visualization is accessible."

6.4. Access is an Experience, not just Compliance

Zhang offered insight into the design intention of Chartability, "[it is] clearly going for above compliance and focusing on a good experience." Sam expressed their need to make an excellent accessibility experience, "I am not just worried about compliance, but I want to make something really good. Nothing seems to help you go beyond? This is better than WCAG, I can already tell."

6.5. Everyone wants More Evaluation Resources and Tools

For constructive feedback, all the data experts noted that they wanted more resources and materials related to learning the skills needed to conduct an audit. Shugart and Moseng both noted that they hope for more tooling and (in some cases) automated tests that can take the burden off the auditor and streamline the design and development process (much like Axe-core [noa21a]). They both also agreed that automation and tooling would help novice practitioners perform this work faster and with more confidence. 2 of the 3 mentioned wanting more examples of failures as well as accessible data experiences. Sam wrote that they felt Chartability was overwhelming at first, but after focusing on just the Critical items, the rest of the framework "became easier."

6.6. Experts: "Novices will Struggle." Novices: "This was so helpful"

The accessibility experts all unanimously agreed that Chartability is helpful to their own work, but they are unsure how accessibility novices would do. They all believe that more training and resources are needed to help people who are new, with one noting that Chartability could even be "overwhelming" to someone who has not been exposed to accessibility work before. All of the novices remarked that Chartability was "so helpful," "made this work so much clearer than before," and "made a lot of hard problems not as hard."

6.7. What about Auditors with Disabilities?

Shugart's feedback was critical when discussing continuing to use Chartability, "I still feel as a screen reader user, the audit itself would have some unique challenges because I'd be missing a lot and would have problems determining things such as color." He continued, "Auditing anything accessibility-wise as a screen reader user poses challenges because you don't always know what you're missing. In many cases there are workarounds to this but datavis is one area where this is really hard to do now."

7. Extended Results

We released Chartability in April of 2021, 11 months before this sentence was written. We made Chartability openly available as a living artifact on Github in order to mitigate risk over time (as a sort of longitudinal artifact). As new research, practices, and feedback emerges as more community members get involved, Chartability will become an evolving artifact of consensus similar to existing standards bodies [noaq].

Projects like Turkopticon benefited from the discussion about how a community actually used their tool [IS13]. In the same vein, we are happy to report some valuable findings from within this last year that we think demonstrate (in a pragmatic way) that Chartability has some merit:

- **It is living and growing**: Chartability has received enough community feedback that it is now on Version 2, with more tests and background resources provided.
- **People are talking about it**: Chartability has been featured in 14 workshops, talks, and podcasts and at least 2 university courses.
- **People are using it**: Chartability has contributed to projects at Microsoft, Highcharts, Project Jupyter, Fizz Studio, FiveThirtyEight, Vega-Lite, UCLA, the City of San Francisco, the Missouri School of Journalism, a fortune 50 company, two Fortune 500 companies, and community groups (like MiR).
- **It has breadth**: Chartability has evaluated static and interactive data experiences made with Microsoft's Excel and PowerBI, Tableau, JavaScript (D3, Vega-Lite, Highcharts, Visa Chart Components), Python (Altair, Bokeh, and matplotlib), R (ggplot2), as well as design sketches and low/medium-fidelity artifacts (Illustrator, Figma, Sketch).

When considering the analysis by Hurst and Kane about high abandonment rates in assistive technology, [HK13] we wanted to make sure that we created an artifact (assistive technology or otherwise) that would at least survive its first year of use in the real world.

The greater community feedback as well as new research before and after open-sourcing Chartability has also led to 5 new tests being added since our test users performed audits and gave evaluations. The current version of Chartability (v2) has a total of 50 tests.

It is important to note that the work of Chartability did not begin and does not conclude with the publication of this manuscript. We want Chartability to become a living, community-driven effort that will adapt and grow as more resources, tools, and research become available. Too much work in the accessibility space ends when a paper is published or project concludes [HK13]. We hope that the work of Chartability will continue.

8. Discussion

From our presentation of Chartability and the preliminary user evaluation, we learned that Chartability reduces the perception that working on accessibility is difficult and increases the confidence of those new to this work. Chartability shows promise as a useful framework for expert accessibility practitioners because it serves to produce consistency in contexts like the evaluation of dashboards, data science workflows, and other complex, data-driven interfaces.

We agree with experts that more resources are needed which provide examples of both inaccessible and accessible data visualizations as well as how to perform some of the more difficult parts of the auditing process (such as evaluating with a screen reader). But we do contend that resources are scarce for accessibility at large, not just visualization.

While our practitioners with novice accessibility experience were initially concerned about doing the audit correctly, most of their audit results were reasonably comparable with that of the authors (although their time to complete was much longer).

Chartability is a valuable tool for auditing. But we also hope that it can inspire researchers to:

1. Examine which heuristics (in our supplemental materials) could use more research attention, particularly those labelled "community practice."
2. Define constraints or requirements on novel projects, ensuring that new explorations still respects established standards, mitigating ethical risks.
3. Explore the intersections of disability in ways yet unaddressed in research and standards.
4. Consider access barriers in data experiences beyond those related to visual perception.
5. Engage the relationship between labor and access in computing.

9. Conclusion

The demand for accessible data experiences is long overdue. The Web Accessibility Initiative's (WAI) Web Content Accessibility Guidelines (WCAG) are over 22 years old and yet little work has been done to synthesize this large body of existing accessibility standards with research and inclusive design principles relevant to the fields of data communication, data science, data analysis, and visualization. Chartability seeks generate a set of heuristics that can fill the gaps in accessibility practice. This synthesis is meant to empower researchers, analysts, designers, developers, editors, and accessibility specialists with a framework to audit the accessibility of data experiences, interfaces, and systems to produce more inclusive environments for users with disabilities. The goal of Chartability is to make this work easier in order to encourage practitioners to regard current practices and resources, some of which have existed for decades.

We believe that our work opens the door to more work that remains to be explored in this space. Additional research is needed into many of the topic areas within Chartability's heuristic principles (POUR+CAF) as well as resources, examples, and tools provided for practitioners to perform this work more confidently and efficiently.

The changing landscape of visualization techniques and alternative interfaces (such as sonification and dynamic tactile graphics) may increase the demands for accessibility considerations in this space. The growing technological divide will become an even greater human rights issue as time moves on and we believe that tools like Chartability are necessary for the community of data practitioners to ensure they are including people with disabilities.

References

[Ald08] ALDRICH F.: Talk to the Hand: An Agenda for Further Research on Tactile Graphics. In *Diagrammatic Representation and Inference* (Berlin, Heidelberg, 2008), Stapleton G., Howse J., Lee J., (Eds.), Lecture Notes in Computer Science, Springer, pp. 344–346. doi:10.1007/978-3-540-87730-1_31. 2

[BBB18] BENNETT C. L., BRADY E., BRANHAM S. M.: Interdependence as a Frame for Assistive Technology Research and Design. In *Proceedings of the 20th International ACM SIGACCESS Conference on Computers and Accessibility* (New York, NY, USA, Oct. 2018), ASSETS '18, Association for Computing Machinery, pp. 161–173. URL: https://doi.org/10.1145/3234695.3236348, doi:10.1145/3234695.3236348. 5

[BC06] BRAUN V., CLARKE V.: Using thematic analysis in psychology. *Qualitative Research in Psychology 3*, 2 (2006), 77–101. URL: https://www.tandfonline.com/doi/abs/10.1191/1478088706qp063oa, arXiv:https://www.tandfonline.com/doi/pdf/10.1191/1478088706qp063oa, doi:10.1191/1478088706qp063oa. 4

[BH12] BROWN C., HURST A.: VizTouch: automatically generated tactile visualizations of coordinate spaces. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction* (New York, NY, USA, Feb. 2012), TEI '12, Association for Computing Machinery, pp. 131–138. URL: https://doi.org/10.1145/2148131.2148160, doi:10.1145/2148131.2148160. 2

[BHR*21] BUTLER M., HOLLOWAY L. M., REINDERS S., GONCU C., MARRIOTT K.: Technology Developments in Touch-Based Accessible Graphics: A Systematic Review of Research 2010-2020. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, May 2021), CHI '21, Association for Computing Machinery, pp. 1–15. URL: https://doi.org/10.1145/3411764.3445207, doi:10.1145/3411764.3445207. 2

[BJJ*10] BIGHAM J. P., JAYANT C., JI H., LITTLE G., MILLER A., MILLER R. C., MILLER R., TATAROWICZ A., WHITE B., WHITE S., YEH T.: VizWiz: nearly real-time answers to visual questions. In *Proceedings of the 23nd annual ACM symposium on User interface software and technology*. Association for Computing Machinery, New York, NY, USA, Oct. 2010, pp. 333–342. URL: https://doi.org/10.1145/1866029.1866080. 2, 3

[BPW15] BORNSCHEIN J., PRESCHER D., WEBER G.: Collaborative Creation of Digital Tactile Graphics. In *Proceedings of the 17th International ACM SIGACCESS Conference on Computers & Accessibility* (New York, NY, USA, Oct. 2015), ASSETS '15, Association for Computing Machinery, pp. 117–126. URL: https://doi.org/10.1145/2700648.2809869, doi:10.1145/2700648.2809869. 2

[Bre02] BREWSTER S.: Visualization tools for blind people using multiple modalities. *Disability and Rehabilitation 24*, 11-12 (Aug. 2002), 613–621. doi:10.1080/09638280110111388. 2

[BRS18] BALAJI A., RAMANATHAN T., SONATHI V.: Chart-Text: A Fully Automated Chart Image Descriptor. *arXiv:1812.10636 [cs]* (Dec. 2018). arXiv: 1812.10636. URL: http://arxiv.org/abs/1812.10636. 2

[BUSC18] BRANGIER E., URRUTIA J. G., SENDEROWICZ V., CESSAT L.: Beyond "Usability and User Experience" , Towards an Integrative Heuristic Inspection: from Accessibility to Persuasiveness in the UX Evaluation A Case Study on an Insurance Prospecting Tablet Application. URL: https://arxiv.org/abs/1806.11291v1. 3

[CC05] CRAFT B., CAIRNS P.: Beyond guidelines: what can we learn from the visual information seeking mantra? In *Ninth International Conference on Information Visualisation (IV'05)* (July 2005), pp. 110–118. ISSN: 2375-0138. doi:10.1109/IV.2005.28. 4

[CC17] CHAPARRO A., CHAPARRO M.: Applications of Color in Design for Color-Deficient Users. *Ergonomics in Design 25*, 1 (Jan. 2017), 23–30. Publisher: SAGE Publications Inc. URL: https://doi.org/10.1177/1064804616635382, doi:10.1177/1064804616635382. 2

[CDC19] CDC: Disability Impacts All of Us Infographic | CDC, Mar. 2019. URL: https://www.cdc.gov/ncbddd/disabilityandhealth/infographic-disability-impacts-all.html. 1

[CJP*19] CHOI J., JUNG S., PARK D. G., CHOO J., ELMQVIST N.: Visualizing for the Non-Visual: Enabling the Visually Impaired to Use Visualization. *Computer Graphics Forum 38*, 3 (2019), 249–260. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/cgf.13686. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/cgf.13686, doi:10.1111/cgf.13686. 2

[CM19] CULLEN C., METATLA O.: Co-designing Inclusive Multisensory Story Mapping with Children with Mixed Visual Abilities. In *Proceedings of the 18th ACM International Conference on Interaction Design and Children* (New York, NY, USA, June 2019), IDC '19, Association for Computing Machinery, pp. 361–373. URL: https://doi.org/10.1145/3311927.3323146, doi:10.1145/3311927.3323146. 2

[CPR*22] CHUNDURY P., PATNAIK B., REYAZUDDIN Y., TANG C., LAZAR J., ELMQVIST N.: Towards Understanding Sensory Substitution for Accessible Visualization: An Interview Study. *IEEE transactions on visualization and computer graphics 28*, 1 (Jan. 2022), 1084–1094. doi:10.1109/TVCG.2021.3114829. 2

[CSA15] CHUAN N. K., SIVAJI A., AHMAD W. F. W.: Usability Heuristics for Heuristic Evaluation of Gestural Interaction in HCI. In *Design, User Experience, and Usability: Design Discourse* (Cham, 2015), Marcus A., (Ed.), Lecture Notes in Computer Science, Springer International Publishing, pp. 138–148. doi:10.1007/978-3-319-20886-2_14. 3

[CZK*19] CHEN C., ZHANG R., KIM S., COHEN S., YU T., ROSSI R., BUNESCU R.: Neural caption generation over figures. In *Adjunct Proceedings of the 2019 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2019 ACM International Symposium on Wearable Computers* (New York, NY, USA, Sept. 2019), UbiComp/ISWC '19 Adjunct, Association for Computing Machinery, pp. 482–485. URL: https://doi.org/10.1145/3341162.3345601, doi:10.1145/3341162.3345601. 2

[CZK*20] CHEN C., ZHANG R., KOH E., KIM S., COHEN S., ROSSI R.: Figure Captioning with Relation Maps for Reasoning. In *2020 IEEE Winter Conference on Applications of Computer Vision (WACV)* (Mar. 2020), pp. 1526–1534. ISSN: 2642-9381. doi:10.1109/WACV45572.2020.9093592. 2

[DeM] DEMARTINI C.: A Tableau Accessibility Journey - Part IV - Keyboard Accessibility. URL: https://www.datablick.com/blog/2021/8/10/a-tableau-accessibility-journey-part-iv-keyboard-accessib 3

[Exp] EXPERIENCE W. L. I. R.-B. U.: 10 Usability Heuristics for User Interface Design. URL: https://www.nngroup.com/articles/ten-usability-heuristics/. 3

[FBT97] FLOWERS J. H., BUHMAN D. C., TURNAGE K. D.: Cross-Modal Equivalence of Visual and Auditory Scatterplots for Exploring Bivariate Data Samples. *Human Factors 39*, 3 (Sept. 1997), 341–351. Publisher: SAGE Publications Inc. URL: https://doi.org/10.1518/001872097778827151, doi:10.1518/001872097778827151. 2

[FJ10] FORSELL C., JOHANSSON J.: An heuristic set for evaluation in information visualization. In *Proceedings of the International Conference on Advanced Visual Interfaces* (New York, NY, USA, May 2010), AVI '10, Association for Computing Machinery, pp. 199–206. URL: https://doi.org/10.1145/1842993.1843029, doi:10.1145/1842993.1843029. 4

[GS11] GALLACE A., SPENCE C.: To what extent do Gestalt grouping principles influence tactile perception? *Psychological bulletin* (2011). doi:10.1037/a0022335. 2

[GSF83] GELDARD F. A., SCHIFF W., FOULKE E.: Tactual Perception: A Source Book. doi:10.2307/1422824. 2

[GSS14] GRAY C. M., STOLTERMAN E., SIEGEL M. A.: Reprioritizing the relationship between HCI research and practice: bubble-up and trickle-down effects. In *Proceedings of the 2014 conference on Designing interactive systems* (New York, NY, USA, June 2014), DIS '14, Association for Computing Machinery, pp. 725–734. URL: https://doi.org/10.1145/2598510.2598595, doi:10.1145/2598510.2598595. 4

[HK13] HURST A., KANE S.: Making "making" accessible. In *Proceedings of the 12th International Conference on Interaction Design and Children* (New York, NY, USA, June 2013), IDC '13, Association for Computing Machinery, pp. 635–638. URL: https://doi.org/10.1145/2485760.2485883, doi:10.1145/2485760.2485883. 10

[Hoa18] HOANG T.: The TableauMagic DataTables Extension Now Available, Sept. 2018. URL: https://tableau.toanhoang.com/the-tableau-magic-datatables-extension-now-available/. 3

[Hon20] HONDULA K.: Shiny App Accessibility, Part 2: Accessible Design, Nov. 2020. URL: https://cyberhelp.sesync.org/blog/shiny-accessibility.html. 3

[IS13] IRANI L. C., SILBERMAN M. S.: Turkopticon: Interrupting worker invisibility in amazon mechanical turk. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2013), CHI '13, Association for Computing Machinery, p. 611–620. URL: https://doi.org/10.1145/2470654.2470742, doi:10.1145/2470654.2470742. 10

[IW] INITIATIVE (WAI) W. W. A.: Accessibility Principles. URL: https://www.w3.org/WAI/fundamentals/accessibility-principles/. 1, 3

[IW21] INITIATIVE (WAI) W. W. A.: Web Accessibility Laws & Policies, Aug. 2021. URL: https://www.w3.org/WAI/policies/. 3

[Jac19] JACKSON T. I. L.: A community response to a #DisabilityDongle, Apr. 2019. URL: https://medium.com/@eejackson/a-community-response-to-a-disabilitydongle-d0a37703d7c2. 2

[JDI*15] JANSEN Y., DRAGICEVIC P., ISENBERG P., ALEXANDER J., KARNIK A., KILDAL J., SUBRAMANIAN S., HORNBÆK K.: Opportunities and Challenges for Data Physicalization. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, Apr. 2015, pp. 3227–3236. URL: https://doi.org/10.1145/2702123.2702180. 2

[JLBJ16] JOYCE G., LILLEY M., BARKER T., JEFFERIES A.: Mobile Application Usability: Heuristic Evaluation and Evaluation of Heuristics. In *Advances in Human Factors, Software, and Systems Engineering* (Cham, 2016), Amaba B., (Ed.), Advances in Intelligent Systems and Computing, Springer International Publishing, pp. 77–86. doi:10.1007/978-3-319-41935-0_8. 3

[JMK*22] JUNG C., MEHTA S., KULKARNI A., ZHAO Y., KIM Y.-S.: Communicating Visualizations without Visuals: Investigation of Visualization Alternative Text for People with Visual Impairments. *IEEE Transactions on Visualization and Computer Graphics 28*, 01 (Jan. 2022), 1095–1105. Publisher: IEEE Computer Society. URL: https://www.computer.org/csdl/journal/tg/2022/01/09552938/1xjQYJDwaxa, doi:10.1109/TVCG.2021.3114846. 2

[JRW*07] JAYANT C., RENZELMANN M., WEN D., KRISNANDI S., LADNER R., COMDEN D.: Automated tactile graphics translation: in the field. In *Proceedings of the 9th international ACM SIGACCESS conference on Computers and accessibility* (New York, NY, USA, Oct. 2007), Assets '07, Association for Computing Machinery, pp. 75–82. URL: https://doi.org/10.1145/1296843.1296858, doi:10.1145/1296843.1296858. 2

[KJRK21] KIM N. W., JOYNER S. C., RIEGELHUTH A., KIM Y.: Accessible Visualization: Design Space, Opportunities, and Challenges. *Computer Graphics Forum 40*, 3 (2021), 173–188. _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. 2

[Lad15] LADNER R. E.: Design for user empowerment. *Interactions 22*, 2 (Feb. 2015), 24–29. URL: https://doi.org/10.1145/2723869, doi:10.1145/2723869. 5

[LCI*20] LEE B., CHOE E. K., ISENBERG P., MARRIOTT K., STASKO J.: Reaching broader audiences with data visualization. *IEEE Computer Graphics and Applications 40*, 2 (2020), 82–90. doi:10.1109/MCG.2020.2968244. 2

[LLJ*20] LAI C., LIN Z., JIANG R., HAN Y., LIU C., YUAN X.: Automatic Annotation Synchronizing with Textual Description for Visualization. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, Apr. 2020, pp. 1–13. URL: https://doi.org/10.1145/3313831.3376443. 2

[LLS19] LUNDGARD A., LEE C., SATYANARAYAN A.: Sociotechnical Considerations for Accessible Visualization Design. *arXiv:1909.05118 [cs]* (Sept. 2019). arXiv: 1909.05118. URL: http://arxiv.org/abs/1909.05118. 2, 3

[LS22] LUNDGARD A., SATYANARAYAN A.: Accessible visualization via natural language descriptions: A four-level model of semantic content. *IEEE Transactions on Visualization and Computer Graphics 28*, 1 (2022), 1073–1083. doi:10.1109/TVCG.2021.3114770. 2

[LTJ86] LEDERMAN S., THORNE G., JONES B.: Perception of texture by vision and touch: multidimensionality and intersensory integration. *Journal of experimental psychology. Human perception and performance* (1986). doi:10.1037//0096-1523.12.2.169. 2

[MB06] MCGOOKIN D. K., BREWSTER S. A.: SoundBar: exploiting multiple views in multimodal graph browsing. In *Proceedings of the 4th Nordic conference on Human-computer interaction: changing roles* (New York, NY, USA, Oct. 2006), NordiCHI '06, Association for Computing Machinery, pp. 145–154. URL: https://doi.org/10.1145/1182475.1182491, doi:10.1145/1182475.1182491. 2

[MBJ85] MANSUR D. L., BLATTNER M. M., JOY K. I.: Sound graphs: A numerical data analysis method for the blind. *Journal of Medical Systems 9*, 3 (June 1985), 163–174. URL: https://doi.org/10.1007/BF00996201, doi:10.1007/BF00996201. 2

[MHK10] MANKOFF J., HAYES G. R., KASNITZ D.: Disability studies as a source of critical inquiry for the field of assistive technology. In *Proceedings of the 12th international ACM SIGACCESS conference on Computers and accessibility* (New York, NY, USA, Oct. 2010), ASSETS '10, Association for Computing Machinery, pp. 3–10. URL: https://doi.org/10.1145/1878803.1878807, doi:10.1145/1878803.1878807. 5

[MJBC18] MORRIS M. R., JOHNSON J., BENNETT C. L., CUTRELL E.: Rich Representations of Visual Content for Screen Reader Users. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, Apr. 2018, pp. 1–11. URL: https://doi.org/10.1145/3173574.3173633. 2

[MLB*21] MARRIOTT K., LEE B., BUTLER M., CUTRELL E., ELLIS K., GONCU C., HEARST M., MCCOY K., SZAFIR D. A.: Inclusive data visualization for people with disabilities: a call to action. *Interactions 28*, 3 (Apr. 2021), 47–51. URL: https://doi.org/10.1145/3457875, doi:10.1145/3457875. 2

[MMJ*21] MACK K., MCDONNELL E., JAIN D., LU WANG L., E. FROEHLICH J., FINDLATER L.: What Do We Mean by

“Accessibility Research”? A Literature Survey of Accessibility Papers in CHI and ASSETS from 1994 to 2019. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, May 2021), CHI '21, Association for Computing Machinery, pp. 1–18. URL: https://doi.org/10.1145/3411764.3445412, doi:10.1145/3411764.3445412. 2

[MSMC14] MORAES P., SINA G., MCCOY K., CARBERRY S.: Evaluating the accessibility of line graphs through textual summaries for visually impaired users. In *Proceedings of the 16th international ACM SIGACCESS conference on Computers & accessibility* (New York, NY, USA, Oct. 2014), ASSETS '14, Association for Computing Machinery, pp. 83–90. URL: https://doi.org/10.1145/2661334.2661368, doi:10.1145/2661334.2661368. 2

[MTS21] MARTÍNEZ R. A., TURRÓ M. R., SALTIVERI T. G.: *Methodology for heuristic evaluation of the accessibility of statistical charts for people with low vision and color vision deficiency*. Tech. rep., Dec. 2021. ISSN: 2693-5015 Type: article. URL: https://www.researchsquare.com/article/rs-156959/v1, doi:10.21203/rs.3.rs-156959/v1. 2, 3

[NAR18] NUÑEZ J. R., ANDERTON C. R., RENSLOW R. S.: Optimizing colormaps with consideration for color vision deficiency to enable accurate interpretation of scientific data. *PLOS ONE 13*, 7 (Aug. 2018), e0199239. Publisher: Public Library of Science. URL: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0199239, doi:10.1371/journal.pone.0199239. 2

[Nie94] NIELSEN J.: Heuristic evaluation. In *Usability inspection methods*. John Wiley & Sons, Inc., USA, June 1994, pp. 25–62. 3

[noaa] Accessibility module | Highcharts. URL: https://highcharts.com/docs/accessibility/accessibility-module. 3

[noab] COVID-19 data and reports | San Francisco. URL: https://sf.gov/resource/2021/covid-19-data-and-reports. 3

[noac] Data visualizations | Visual design | Accessibility for Teams. URL: https://accessibility.digital.gov/visual-design/data-visualizations/. 3

[noad] Everything You Never Wanted to Know About Google Maps' Parameters. URL: https://moz.com/blog/everything-you-never-wanted-to-know-about-google-maps-parameters. 5

[noae] Fixed placement columns | Highcharts.com. URL: https://www.highcharts.com/demo/column-placement. 8

[noaf] Guidelines and Standards for Tactile Graphics. URL: http://www.brailleauthority.org/tg/. 2, 3

[noag] Improving Accessibility in Unity Games – Part 1. URL: https://www.raywenderlich.com/5783444-improving-accessibility-in-unity-games-part-1. 3

[noah] Inclusive Design Principles. URL: https://inclusivedesignprinciples.org/. 5

[noai] mapbox-gl. URL: https://www.npmjs.com/package/mapbox-gl. 3

[noaj] The Naked Truth. URL: https://pudding.cool/2021/03/foundation-names. 8

[noak] Power BI Accessibility Best Practices. URL: https://rklein324.github.io/PowerBIAccessibility/. 3

[noal] Revealing Room for Improvement in Accessibility within a Social Media Data Visualization Learning Community. URL: https://silvia.rbind.io/talk/2021-05-04-data-viz-accessibility/. 3

[noam] SAS Graphics Accelerator Customer Product Page. URL: https://support.sas.com/software/products/graphics-accelerator/. 3

[noan] Semiotic. URL: https://semiotic.nteract.io/guides/accessibility. 3

[noao] Tactile Mapping. URL: http://www.tactilebooks.org/tactileguidelines/page1.htm. 2, 3

[noap] visa-chart-components/packages/utils at master · visa/visa-chart-components. URL: https://github.com/visa/visa-chart-components. 3

[noaq] W3C Accessibility Guidelines (WCAG) 3.0. URL: https://www.w3.org/TR/wcag-3.0/. 10

[noar] We played 20 games to test whether or not our results would end up close to the probability of flipping a coin. URL: https://public.tableau.com/views/CoinFlipGame/CoinFlipGame. 8

[noas] Web Content Accessibility Guidelines (WCAG) 2.1. URL: https://www.w3.org/TR/WCAG21/. 2, 3

[noat] Why Accessibility Is at the Heart of Data Visualization | by Doug Schepers | Nightingale | Medium. URL: https://medium.com/nightingale/accessibility-is-at-the-heart-of-data-visualization-64a38 5

[noa16] Extensive digitization of tactile map collection, July 2016. URL: https://www.perkins.org/extensive-digitization-of-tactile-map-collection/. 2

[noa18a] Are plotly tables accessible? - Graphing Libraries / Plotly.js, Feb. 2018. URL: https://community.plotly.com/t/are-plotly-tables-accessible/8263. 3

[noa18b] Making Shiny apps accessible for all humans - shiny, May 2018. URL: https://community.rstudio.com/t/making-shiny-apps-accessible-for-all-humans/8458. 3

[noa18c] Unlocking Accessibility for UX/UI Designers, Dec. 2018. Section: 2018. URL: https://www.24a11y.com/2018/unlocking-accessibility-for-ux-ui-designers/. 3

[noa19] [SOLVED] Datatables and Accessibility - Dash, Nov. 2019. URL: https://community.plotly.com/t/solved-datatables-and-accessibility/31085. 3

[noa21a] axe-core, Aug. 2021. original-date: 2015-06-10T15:26:45Z. URL: https://github.com/dequelabs/axe-core. 9

[noa21b] mapbox/mapbox-gl-accessibility, Aug. 2021. original-date: 2017-11-16T14:34:49Z. URL: https://github.com/mapbox/mapbox-gl-accessibility. 3

[noa21c] Study Shows Its Automated Testing Identifies 57 Percent of Digital Accessibility Issues, Mar. 2021. URL: https://www.deque.com/blog/automated-testing-study-identifies-57-percent-of-digital- 1

[OH20] OBEID J., HOQUE E.: Chart-to-Text: Generating Natural Language Descriptions for Charts by Adapting the Transformer Model. *arXiv:2010.09142 [cs]* (Nov. 2020). arXiv: 2010.09142. URL: http://arxiv.org/abs/2010.09142. 2

[Oli13] OLIVEIRA M. M.: Towards More Accessible Visualizations for Color-Vision-Deficient Individuals. *Computing in Science Engineering 15*, 5 (Sept. 2013), 80–87. Conference Name: Computing in Science Engineering. doi:10.1109/MCSE.2013.113. 2, 4

[Org] ORGANIZATION W. H.: World report on vision. URL: https://www.who.int/publications-detail-redirect/9789241516570. 1

[OS22] OLIVEIRA M. R. D., SILVA C. G. D.: Adapting Heuristic Evaluation to Information Visualization - A Method for Defining a Heuristic Set by Heuristic Grouping. pp. 225–232. URL: https://www.scitepress.org/Link.aspx?doi=10.5220/0006133202250232. 4

[Ote17] OTEY D. Q.: A methodology to develop usability / user experience heuristics. In *Proceedings of the XVIII International Conference on Human Computer Interaction* (New York, NY, USA, Sept. 2017), Interacción '17, Association for Computing Machinery, pp. 1–2. URL: https://doi.org/10.1145/3123818.3133832, doi:10.1145/3123818.3133832. 3

[QKD*21] QIAN X., KOH E., DU F., KIM S., CHAN J., ROSSI R. A., MALIK S., LEE T. Y.: Generating Accurate Caption Units for Figure Captioning. In *Proceedings of the Web Conference 2021*. Association for Computing Machinery, New York, NY, USA, Apr. 2021, pp. 2792–2804. URL: https://doi.org/10.1145/3442381.3449923. 2

[SB20] SOUTH L., BORKIN M.: *Generating Seizure-Inducing Sequences with Interactive Visualizations*. Tech. rep., OSF Preprints, Oct. 2020. type: article. URL: https://osf.io/85gwy/, doi:10.31219/osf.io/85gwy. 2

[SC99] SLAVKOVIC A., CROSS K.: Novice heuristic evaluations of a complex interface. In *CHI '99 Extended Abstracts on Human Factors in Computing Systems* (New York, NY, USA, May 1999), CHI EA '99, Association for Computing Machinery, pp. 304–305. URL: https://doi.org/10.1145/632716.632902, doi:10.1145/632716.632902. 3

[Sch] SCHNEIDER J.: Constructing the Yellow Brick Road: Route Bricks on Virtual Tactile Maps. 2

[Sch11] SCHOLTZ J.: Developing guidelines for assessing visual analytics environments. *Information Visualization 10*, 3 (July 2011), 212–231. Publisher: SAGE Publications. URL: https://doi.org/10.1177/1473871611407399, doi:10.1177/1473871611407399. 4

[SCWR21] SHARIF A., CHINTALAPATI S. S., WOBBROCK J. O., REINECKE K.: Understanding Screen-Reader Users' Experiences with Online Data Visualizations. 16. 2, 3

[SF18] SHARIF A., FOROURAGHI B.: evoGraphs — A jQuery plugin to create web accessible graphs. In *2018 15th IEEE Annual Consumer Communications Networking Conference (CCNC)* (Jan. 2018), pp. 1–4. ISSN: 2331-9860. doi:10.1109/CCNC.2018.8319239. 2

[SHW21] SCHAADHARDT A., HINIKER A., WOBBROCK J. O.: Understanding Blind Screen-Reader Users’ Experiences of Digital Artboards. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, May 2021), CHI '21, Association for Computing Machinery, pp. 1–19. URL: https://doi.org/10.1145/3411764.3445242, doi:10.1145/3411764.3445242. 2

[sim20] SIMON: Making Graphs And Plots Accessible For The Blind, June 2020. URL: https://andadapt.com/making-graphs-and-plots-accessible-for-the-blind/. 3

[SSB21] SOUTH L., SAFFO D., BORKIN M.: *Detecting and Defending Against Seizure-Inducing GIFs in Social Media*. Tech. rep., OSF Preprints, Jan. 2021. type: article. URL: https://osf.io/4kgu6/, doi:10.31219/osf.io/4kgu6. 2

[SSD18] SANTOS B. S., SILVA S., DIAS P.: Heuristic Evaluation in Visualization: An Empirical Study : Position paper. In *2018 IEEE Evaluation and Beyond - Methodological Approaches for Visualization (BELIV)* (Oct. 2018), pp. 78–85. doi:10.1109/BELIV.2018.8634108. 3, 4

[SZFA16] SHI L., ZELZER I., FENG C., AZENKOT S.: Tickers and Talker: An Accessible Labeling Toolkit for 3D Printed Models. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, May 2016, pp. 4896–4907. URL: https://doi.org/10.1145/2858036.2858507. 2

[WKG*11] WOBBROCK J. O., KANE S. K., GAJOS K. Z., HARADA S., FROEHLICH J.: Ability-Based Design: Concept, Principles and Examples. *ACM Transactions on Accessible Computing 3*, 3 (Apr. 2011), 9:1–9:27. URL: https://doi.org/10.1145/1952383.1952384, doi:10.1145/1952383.1952384. 5

[WPA*21] WU K., PETERSEN E., AHMAD T., BURLINSON D., TANIS S., SZAFIR D. A.: Understanding Data Accessibility for People with Intellectual and Developmental Disabilities. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, May 2021), CHI '21, Association for Computing Machinery, pp. 1–16. URL: https://doi.org/10.1145/3411764.3445743, doi:10.1145/3411764.3445743. 2

[XVWF20] XIONG C., VAN WEELDEN L., FRANCONERI S.: The Curse of Knowledge in Visual Data Communication. *IEEE Transactions on Visualization and Computer Graphics 26*, 10 (Oct. 2020), 3051–3062. Conference Name: IEEE Transactions on Visualization and Computer Graphics. doi:10.1109/TVCG.2019.2917689. 6

[ZPSL08] ZHAO H., PLAISANT C., SHNEIDERMAN B., LAZAR J.: Data Sonification for Users with Visual Impairment: A Case Study with Georeferenced Data. *ACM Transactions on Computer-Human Interaction 15*, 1 (May 2008), 4:1–4:28. URL: https://doi.org/10.1145/1352782.1352786, doi:10.1145/1352782.1352786. 2