DOI: 10.1111/cgf.14298
Eurographics Conference on Visualization (EuroVis) 2021
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(Guest Editors)

Volume 40 (2021), Number 3

Accessible Visualization: Design Space, Opportunities, and Challenges

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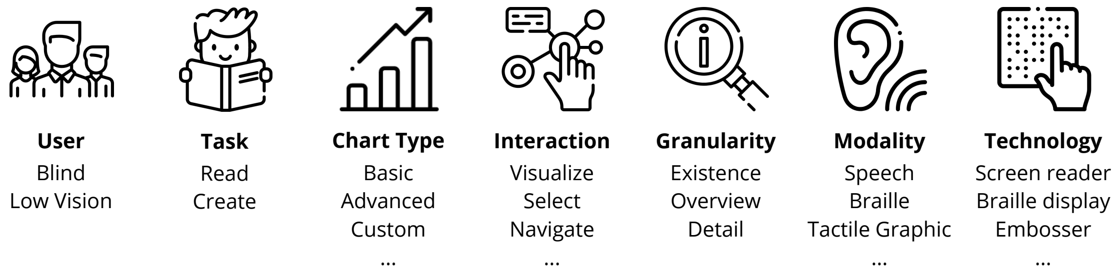


Figure 1: *Seven design dimensions of accessible visualizations: target user, literacy task, chart type, interaction, information granularity, sensory modality, and assistive technology. Icons made by Freepik from* `www.flaticon.com`

Abstract

Visualizations are now widely used across disciplines to understand and communicate data. The benefit of visualizations lies in leveraging our natural visual perception. However, the sole dependency on vision can produce unintended discrimination against people with visual impairments. While the visualization field has seen enormous growth in recent years, supporting people with disabilities is much less explored. In this work, we examine approaches to support this marginalized user group, focusing on visual disabilities. We collected and analyzed papers published for the last 20 years on visualization accessibility. We mapped a design space for accessible visualization that includes seven dimensions: user group, literacy task, chart type, interaction, information granularity, sensory modality, assistive technology. We described the current knowledge gap in light of the latest advances in visualization and presented a preliminary accessibility model by synthesizing findings from existing research. Finally, we reflected on the dimensions and discussed opportunities and challenges for future research.

CCS Concepts

• ***Human-centered computing*** → ***Visualization; Accessibility;***

1. Introduction

As our society is becoming data-driven, visualizations have gone mainstream. People from diverse backgrounds such as scientists, journalists, government employees frequently use visualizations to understand complex data and convey important messages to the public. Charts and graphs are becoming essential for general education as the ability to work with data, also known as data literacy, is becoming a vital skill for everyone [Shr18]. By leveraging our visual perception, visualizations enable us to grasp the implications of data without requiring advanced statistical literacy, contributing to its wide adoption across disciplines.

Although the visualization field has grown dramatically in recent years, research on inclusive and accessible visualization design currently lags behind the pace of this growth [LCI*20]. Visualization accessibility is still not considered as a standalone visualization sub-discipline. Not only are there few papers about accessibility in the premiere conferences in visualization such as VIS and EuroVis, but also these conferences currently do not provide any submission keywords for accessibility [vis]. While supporting the general public has long been part of visualization research, researchers are relatively recently acknowledging the importance of addressing accessibility.

Visualizations have unique challenges in making them accessible due to their structure and content. As a result, assistive technology for regular images may not work for visualization images. Moreover, recent visualizations are more complex and dynamic, delivering millions of data points through intricate visual encodings and interactions. Addressing these challenges is more critical than ever. According to recent research in 2017 [BFB*17], around 36 million people were estimated to be blind (∼0.4% of the global population), while approximately 217 million people had moderate to severe visual impairment (∼3%). The numbers are growing with the growth and aging of the world's population. The increasing barriers to access visualizations can widen the information gap for the blind and visually impaired.

Our goal is to investigate the current knowledge gap in accessibility research in visualization. We surveyed existing research on visualization accessibility. We collected research papers published since 1999 by formulating a search query containing related keywords such as visualization, accessibility, and visual impairment. We excluded papers that focus on color deficiency and non-data visualizations such as general diagrams and regular maps without quantitative data, resulting in a total of 56 papers. We performed thematic analysis through open coding of the paper collection and derived a design space for accessible visualization.

Our design space (Figure 1) includes seven dimensions: *target users*—blind, low-vision, sighted, *task*—read, write, *chart type*—basic statistics charts to advanced visualizations, *interaction*—visualize, filter, select, and navigate, etc., *information granularity*—existence, overview, detail, *sensory modality*—braille, haptic, sonification, tactile graphic, etc., *assistive technology*—screen readers, tactile printers, etc. We describe what each dimension entails and contrast the current state with the recent advances in visualization research.

We also present a preliminary accessibility model that synthesizes and extrapolates findings from artifacts and empirical studies in our paper collection. The model follows the user's flow of information processing as its primary axis and has four stages: 1) notifying the chart existence, 2) giving an overview, 3) providing details on demand, 4) bringing context when needed. We incorporate relevant design considerations for different modalities in each stage of the model. The model serves as an initial baseline but has much room for expansions to address the complexity and interactivity of visualizations we face today.

The design space and the model provide a conceptual framework for comparing and evaluating accessible visualizations. Based on the lessons learned, we discuss challenges and opportunities for future research. These include establishing accessibility guidelines tailored for visualization design, supporting diverse users and visualizations, developing generalizable and affordable methods to ensure visualization accessibility, and bridging knowledge between different sensory perceptions beyond visual perception.

2. Background

The Web is a primary channel for people to access information. W3C's Web Accessibility Initiative (WAI) established the Web Content Accessibility Guidelines (WCAG) in 1999 [WCAb]. The guidelines outline four accessibility principles—perceivable, operable, understandable, and robust—so that people with disabilities (e.g., motor, visual, cognitive impairment) can equally navigate and interact with websites. The WAI provides guidelines for content producers, along with examples describing the provision of alternative text [WAI]. Alt-text translated into accessible forms such as braille or speech is a de facto standard for non-text content. Many countries enact laws and policies to ensure accessibility [WCAa].

Accessibility is widely investigated in the field of human-computer interaction, from user experience studies to the development of new assistive technologies [HY08]. Frequently cited frustrations from blind users when browsing the web include inappropriate or absent labels, confusing layouts, and missing links [LAKM07]. While their browsing behavior is similar to sighted users, they are less likely to tolerate dynamic page content not addressed well by assistive technologies. The W3C guidelines have not proven sufficient in combating these issues [PFPS12].

Websites have become increasingly complex and also progressively inaccessible over the past years [HPZ03]. The web content has become more diverse such as social media [GCC*19] and documents with emoji [TGM20], as with technologies such as touchscreen [MBJ08] and AR/VR [ZHHA17], bringing additional accessibility challenges. Recent research attempts to quantitatively evaluate accessibility and develop automatic methods to improve accessibility, such as using AI [WWFS17] or crowdsourcing [BJJ*10].

A major problem that visually impaired people face is the accessibility of images through screen reader [MJBC18]. When the screen reader encounters an image or non-text element, it will read the alternative text embedded into the element. However, the alternative text is often not helpful or not present at all, rendering the image inaccessible to the users [MJBC18]. This problem can be exemplified in the context of Twitter images, with only 0.1 percent of Twitter images having alternative text and 17 percent of these descriptions being completely irrelevant to the image [GCC*19].

Traditional fields such as cartography and diagrams have investigated accessibility issues. For instance, Hennig et al. [HZW17] provide an overview of approaches for accessible maps, including recommendations for designing interfaces and interactions (e.g., labeling map elements and providing verbal descriptions). Wabiński and Kuźma compare the effectiveness of tactile map techniques [WMK20]. Lawrence and Lobben [LL11] discuss ways for encoding information into discriminable symbols for tactile maps, such as varying the spacing between tactile dots to simulate the effect of lighter or darker color. On the other hand, Torres and Barwaldt provide a survey of existing methods for accessible diagrams, discussing which approaches alternative modalities and devices used [TB19].

Although these past studies may provide useful insights into accessible data visualizations, their results are not directly transferable. Data-driven visualizations pose unique challenges for making the complex yet systematic visual encoding of data accessible, as well as its interactive manipulations. There have been several studies for data visualization accessibility hither and thither. However, it has not been part of the mainstream visualization research and thus has not been kept up to date with the field's recent advancements. Our survey in this work analyzes the past work and highlights the knowledge gap in visualization accessibility.

3. Methodology

To understand the current state of research in visualization accessibility, we conducted a systematic analysis of the existing literature, inspired by the grounded theory approach [SC97, WM19]. Figure 2 shows the overview of our data collection and analysis process.

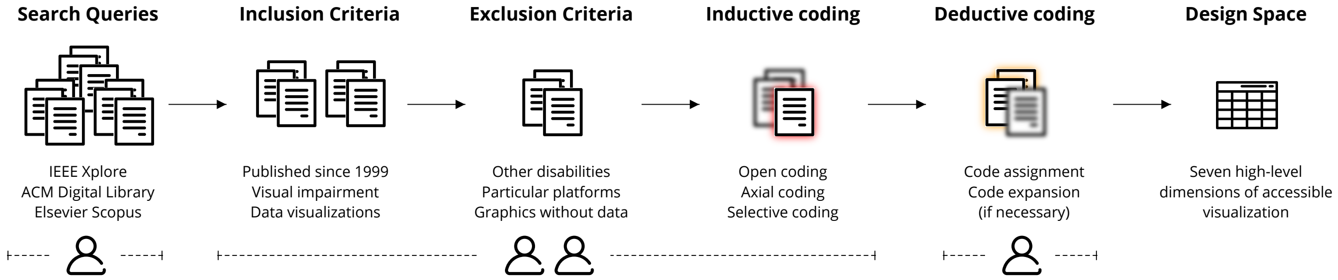


Figure 2: *Overview of the data collection and analysis process. A researcher formulated structured queries to search over publication archives. Two researchers applied inclusion and exclusion criteria to derive the final paper collection and inductively settled on a stable consensus set of codes. One of the researchers validated the codes by applying them to the remaining papers. The final design space was derived and agreed upon by the two researchers. Icons made by Freepik from* `www.flaticon.com`

3.1. Data Collection

We collected papers from digital libraries, including the IEEE Xplore, the ACM Digital Library, and the Elsevier Scopus database. We searched titles, abstracts, and keywords of research papers published since 1999. We limited our analysis to papers published since 1999 given technological relevance to today's digital environment. Our search used boolean search queries with multiple search terms within the categories of visualization, accessibility, and visual impairment. We used the following query for searching Scopus and similar variants for IEEE and ACM.

```
( ( TITLE-ABS-KEY ( ( "visualization" OR "visualisation"
OR graph OR chart ) AND ( "accessibility" OR "accessi-
ble" ) AND ( "visual* impair*" OR blind ) ) AND PUBYEAR
> 1998 ) )
```

To avoid missing papers from key conferences and journals, we also specifically searched IEEE TVCG, CHI, ASSETS, CSCW, and CGF (EuroVis) using a broader search query with keywords in the same categories. The final search was concluded in November 2020. We combined the search results and removed duplicates, resulting in an initial corpus of 413 publications.

We guided our final selection of the papers from the initial corpus by applying inclusion and exclusion criteria. We inspected the initial corpus, including titles, abstracts, and main texts if necessary, to evaluate whether the criteria allowed for a well-balanced search or whether we needed to revise the initial search query. Through multiple iterations to reach the final collection, two researchers evaluated each article on its conformance to the following inclusion criteria:

- Focusing on accessibility and visual impairment
- Addressing the accessibility of data-driven visualizations

We then flagged each article when meeting the following exclusion criteria:

- Focusing on other types of impairments
- Focusing on physical places or specific hardware/software
- Addressing non-data visualizations such as graphical diagrams and illustrations
- Artifacts already reported in another publication
- Non-archival research posters

Based on the exclusion criteria, we did not consider color deficiency as it is relatively well-known in the community and excluded non-data graphics such as plain maps without quantitative data and generic diagrams except network graphs. The final collection consists of 56 papers.

3.2. Thematic Analysis through Open Coding

Two researchers went through an iterative coding process to derive orthogonal design dimensions of accessible visualization.

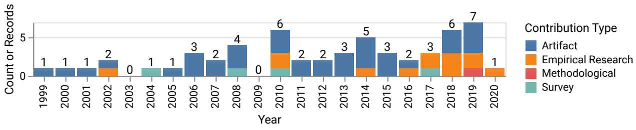
The researchers inductively derived a stable consensus set of codes by inspecting a few random sampled papers through open, axial and selective coding. That is, they identified emergent themes and codes as they analyzed the selected set of papers. They then categorized the codes based on relevance Table 1 and further grouped them into higher-level dimensions. Any conflict was resolved, and a consensus was reached on demand until both researchers' coding was consistent.

After reaching the consensus set of codes and dimensions, one researcher deductively applied the codes to the rest of the papers. Although it rarely occurred, if the researcher observed new concepts, they revised the codes as necessary. To a certain extent, this deductive process evaluated the validity of the codes. In the end, this process resulted in seven design dimensions along with relevant codes as shown in Figure 4. We explain the dimensions and codes in Section 4.

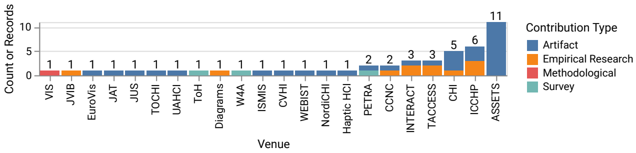
3.3. Preliminary Overview of Final Data

Figure 3 shows the number of publications by year and by venue. We observed a small increasing trend over the past two decades. ACM ASSETS (11/56) was the most popular venue, while only three papers are from dedicated visualization conferences, including VIS (1/56) and EuroVis (1/56). The three papers were published only recently, from 2018 to 2020.

To further understand the composition of research contributions made among these publications, we classified the publications using the taxonomy from Wobbrock and Kientz [WK16]. The most frequent contribution type was artifact (38/56), while empirical research is the next (13/56). The four existing surveys are different from ours in that they focus on specific accessible modalities such as haptics [EW17a, PR10] or analysis of existing charts [EW17a, BSP04, FBV*08], not the research literature.



(a) *The number of papers by year, broken down by contribution type. The chart shows a slight increasing trend.*



(b) *The number of papers by venue, broken down by contribution type. ASSETS is the most popular venue, while VIS and EuroVis have low numbers.*

Figure 3: *Overview of the collected papers used for constructing the design space*

4. Design Space

Figure 4 shows an overview of the design space. The design dimensions broadly fall into three categories: *why* it is accessible — supported users and tasks, *what* is accessible—charts and interactions, and *how* it is accessible—level of information details, sensory modalities, and assistive technologies. We describe each dimension's definition, the current state of support, and the knowledge gap in contrast to the recent advances in visualization.

4.1. User

Unlike typical audiences of data visualizations, people with visual impairment have unique needs. They may not fully leverage the sense of sight that offers a unique information processing bandwidth such as pre-attentive processing and visual pop-out, while such global processing through other senses such as haptics can be overcome to some degree with sufficient training [PJV14]. The term **visual impairment** refers to reduced visual acuity of the visual field, ranging from blindness to low vision. The decreased visual function interferes with daily abilities such as reading and driving. There are various vision symptoms as blurred vision, loss of central or peripheral vision, and extreme light sensitivity [The]. Figure 5 show simulated examples of seeing a visualization image with vision disabilities.

According to the International Classification of Diseases (ICD) published by WHO [idc], **Blindness** is defined as visual acuity worse than 3/60. It means a visually impaired person would have to come at least within 3 meters to see a target clearly when the average sighted could sharply see the same target from 60 meters away. The definition of *legally* blind may differ from country to country; for example, in the U.S., it is defined as visual acuity less than 6/60. **Low-vision** refers to impaired visual acuity that cannot be corrected by regular glasses. According to ICD, A person with the best-corrected visual acuity of worse than 6/12 or 6/18 is considered to have a mild to moderate visual impairment, while visual acuity of less than 6/60 means a severe vision impairment.

We observed that most papers in our collection do not necessarily distinguish the various types of visual impairments. They use blindness (32/56) and visual impairment (32/56) interchangeably and focus on addressing the absence of vision using alternative sensory modalities such as audio and touch. A few studies briefly discuss low-vision or involve low-vision participants but do not address the specific needs of this population [GMSK19, YMB*20, ADL*02]. Rare examples are the two studies in which one briefly mentions highlighting and magnification synchronized with screen reading [GMS18] and another one compares experiences of totally blind and partially sighted participants in using an audio-haptic device [AAH14].

Interestingly, sighted users (5/56) were often part of the target audience. They were mainly teachers who need to create accessible visualizations [BMS*14, WAYM16, TBC*16] or annotate an existing one with accessible information [FM15] to teach visually impaired students. Often, teachers themselves were visually impaired [AAH14], indicating a distinctive need for the ability to create visualizations.

The visualization user base has been expanded to journalists, designers, and casual users who often focus on communication [LRIC15] or have personal data needs [TLCC17]. As more diverse groups of (sighted) users appreciate the value of visualization, more research has been carried out to better support their specific needs based on their personality [ZCY*11] or cognitive trait [TCSC13]. However, our investigation reveals a significant gap in *understanding the needs and motivations of people with different types of visual impairments*, which must be the first step toward addressing this particular user group.

4.2. Task

Reading and creating visualizations are the two distinct higher-order literacy tasks we observed, each of which is essential for visualization literacy [BBG19]. The reading task groups all tasks corresponding to the ability to understand the meaning of visualizations (44/56), while creating refers to tasks requiring the ability to construct visualizations on their own (12/56). Reading a visualization involves perceiving visual and textual elements using alternative sensory channels, for example, retrieving specific values from a tactile bar chart. Creating, on the other hand, requires interacting with user interface components to specify visual encodings. The latter is much more nuanced to support, and relatively few papers tackle this task. Figure 6 shows two example tools for creating accessible visualizations.

We found that a majority of the papers are published outside the major visualization conferences and thus do not follow, or are not aware of, the established task vocabularies in the visualization field [LPP*06, BM13]. It is now well known that tasks play an important role in determining the effectiveness of a visualization [SED18, KH18]. Our analysis suggests the current *lack of understanding on what visualization tasks visually impaired people primarily perform and how differently they perform the tasks using non-visual channels*. A better understanding of non-visual tasks will be necessary to inform the effective design of accessible visualizations.

4.3. Chart Type

Most studies do not go beyond basic statistical plots such as bar charts, line charts, pie charts, and scatter plots that take up around

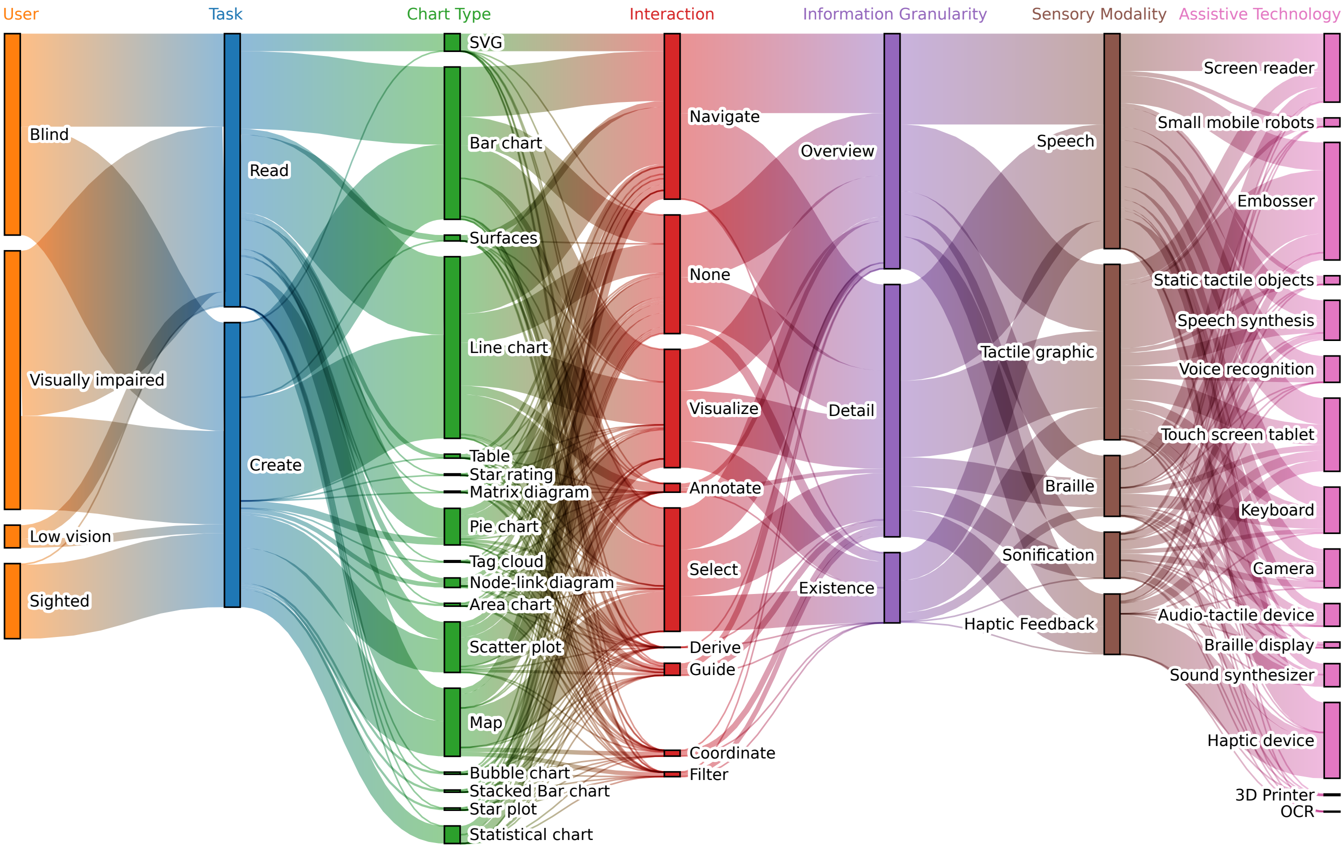


Figure 4: *A sankey diagram showing the proportional relationship among design dimensions. The dimensions are arranged based on a design process of an accessible visualization: user, task, chart type, interaction, granularity, modality, and technology.*

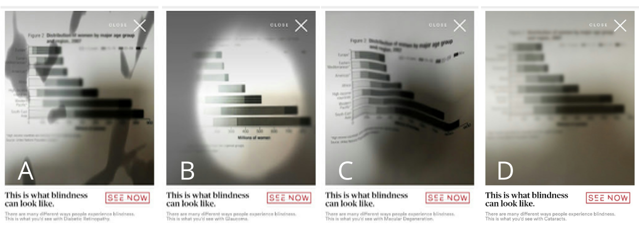


Figure 5: *(A) Clouded and spotted vision as caused by Diabetic Retinopathy, (B) loss of peripheral vision as caused by Glaucoma, (C) loss of central vision as caused by Macular Degeneration and (D) blurry vision as caused by Cataracts, generated using See Now's sight loss simulator [Now]*

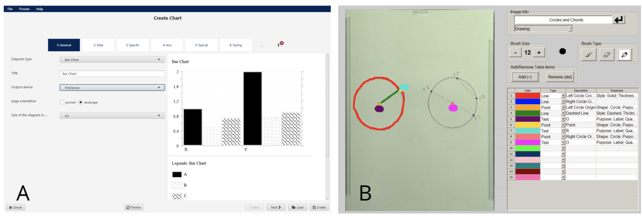


Figure 6: *(A) SVGPlott [WM10] providing an accessible interface for creating audio-tactile charts in SVG format. (B) Tactile graphics helper [FM15] allowing for annotating a tactile chart with additional audio-based information.*

80% of all charts. Some of the advanced charts, such as statistical maps (6/56) and network graphs (4/56), were also common. While most papers focus on a few selected charts, two of them present more generalizable accessibility methods across different chart types. ASVG [WOH*15] adds accessible information using custom attributes in SVG elements and supports navigating the information by following the hierarchical structure of the elements. Godfrey et al. [GMS18] similarly used annotated SVG to support accessible navigation of the underlying chart structure.

While the popularity of the standard charts still persists today, we have seen an enormous growth of more advanced visualizations such as spatio-temporal visualizations [BDA*14] and multivariate dynamic networks [NSML19]. We also see a plethora of innovative custom and personal visualizations in the wild such as in data journalism and visual arts, which might involve non-traditional marks and layouts. The visual complexity of modern visualizations poses a significant challenge for accessibility. In particular, for those new visualizations, there is *no consensus on what information needs to be accessible and the order of their importance, as well as no understanding of how visually impaired people make sense of the unfamiliar visualizations* [LKH*15].

4.4. Interaction

A significant portion of our collection does not address interactions (∼52%) and focuses on static visualizations. This is particularly true for tactile graphics on paper. To categorize types of interactions supported, we used the existing interaction taxonomy by Heer & Shneiderman [HS12]. *Navigate* (21/56) was the most common interaction and mainly used to support the navigation of elements within a chart rather than across multiple charts, such as using keyboards to move between value labels. *Visualize* (8/56) was the primary interaction for systems that support creating a chart. We observed *Derive* (1/56), *Filter* (2/56), and *Guide* (2/56) only in reading tasks. For instance, ChartMaster [ZT15a] presents a guided structure for users to query and filter data to explore stock market data. Similarly, Doush et al. [DPSS10] support guidance (attraction forces towards data points) to assist with navigating chart content. While not frequently, we also observed *Coordinate* (2/56) and *Select* (5/56) such as switching between different sonified maps [LCC*13] or selecting items to highlight and trigger verbal feedback on the items [FM15].

As with increasingly complex chart types, interactive visualizations are now increasingly popular. Manipulating visualizations through common user interface elements such as buttons and drop-downs might be supported through available assistive technologies such as screen readers, as we observed a few in our collection (e.g., ChartMaster [ZT15a]). However, it is still *unclear how to make advanced interactions accessible, such as multiple-coordinated views and in-visualization interactions* (e.g., brushing and zooming [MGRG07]). It is also possible that the benefit of interactions may not hold true for visually impaired users, as they add an additional layer of complexity. *Understanding how they think of interactions* might be a first step to tackle this issue [GTS10].

4.5. Information Granularity

Information granularity refers to the amount of detail conveyed in a visualization. This dimension reflects the needs of users who might want an overview while others wish to explore details [ADL*02]. On the most basic level, a user only receives information on the *existence* of a chart but no information on the underlying dataset (6/56). Users may come across these alerts when visualization images use generic alt-text such as "Chart" [SMG20]. This notification is often necessary since charts are typically embedded in other media such as news articles and slideshows.

On the next level, an *overview* helps to grasp the general idea of a chart (47/56). The overview includes the summary of the content such as a title, axis titles, legends, and the structure such as data distributions, orientation, and appearance of the chart. However, it may not include individual data values. The highest level of granularity is reached when *details* that allow the inference of the precise values and groupings are provided (38/56). Most systems provide these details on an on-demand basis through interactive navigation such as using a keyboard [SF18, Hah15]. The combination of overview and detail was the most common pattern we observed (Figure 7).

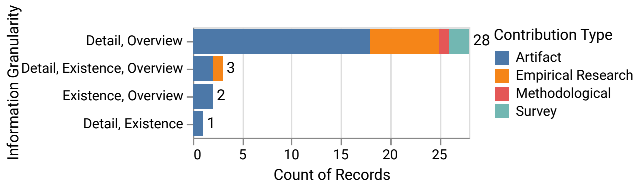


Figure 7: *Different levels of information granularity are combined together. Overview + detail is the most common combination.*

The granularity dimension provides useful guidance on how we can scaffold the accessible information in order. We observed that there is currently *a lack of consensus and guidance on how to structure information within each level*. Recent studies on improving chart titles [BBK*15, MHSW19] could be useful for writing a good overview, although much research is *missing to understand what makes a good visualization description*. Likewise, *supporting efficient exploration of details without being stuck and overwhelmed* would be a challenging problem to address.

4.6. Sensory Modality

Visualizations rely on vision as a main sensory channel. A critical design choice for accessible visualizations lies in selecting alternative sensory modalities. Most sensory channels we observed leverage audio perception and tactile perception.

Auditory perception supports speech (40/56) and sonification (16/56) modalities. Speech is the most common and low-cost accessible modality. For instance, EvoGraphs is a web-based system and generates a screen reader accessible description which does not require special hardware [SF18]. Many other systems also work on the web and generate navigable text descriptions using keyboards [ESC*07, CJP*19a, MPS17]. On the other hand, sonification uses non-speech audio to convey data. We observed almost all cases use a pitch variation to indicate an increase or decrease in a data value (e.g., a line graph [CW10a]). This may allow users to gain a quick overview of a graph, although precise values can not be conveyed if no reference point is provided verbally.

An empirical study showed that participants prefer speech over sonification because cognitive overload for a sonified graph is subjectively higher [SJJ19]. Both speech and sound are serially processed, and thus it is currently unclear how they might generalize to visualizations involving intricate patterns and large datasets [FLST13]. For speech, prolonged descriptions can be frustrating and should be accessed only when required (`alt` for overview and `longdesc` for details in a HTML image tag) [ADL*02]. So far, there is *no agreement on how to structure long chart descriptions* [ADL*02]. Likewise, there seems to be a lack of clear understanding of the rankings of mappings from sound dimensions (e.g., pitch, amplitude, tempo) to data dimensions (e.g., size) [WM10].

Tactile perception mainly utilizes tactile graphics such as embossed prints and physical visualization (19/56), haptic feedback such as forced vibrations (15/56), and braille for texts (7/56). For many visually impaired users, perceiving information through

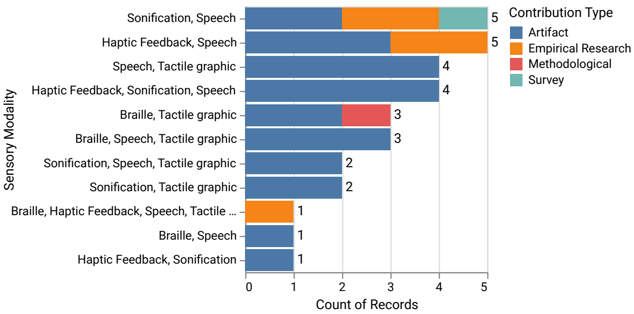


Figure 8: *Rankings of combinations of multiple modalities. Speech in combination with non-verbal cues such as sonification and haptic feedback are the most integration approaches.*

touch is common, particularly in an educational context [EW17b], and its spatiality allows simultaneous and on-demand exploration of data trends in contrast to linear audio [EW18]. However, it requires motor movement and lacks the bandwidth to support the pre-attentive processing of multiple elements in a visualization. Also, it is challenging to represent and perceive intricate structures; that is, it requires a larger space for high-resolution information.

In tactile graphics, heavy guidelines (e.g., grids) can hamper the efficient perception of data, as with overwhelming content and ambiguous textures that are used in place of color [EW17b, EW17a, YMB*20]. Grasping a chart's orientation is also crucial for a visually impaired user to successfully understand the visualization [EW17b]. Braille labels are usually accompanied to convey precise values and textual elements such as legends. A study demonstrated that a tactile scatter plot enables faster reading of a correlation pattern compared to a braille-based table and speech-based table [WM18], although different chart types can lead to different user experiences and preferences [EW18, EW17a]. The haptic modality is absent of a tactile graphic's physicality but uses force feedback to interact with a virtual graphic. Paneels et al. provide a comprehensive review of designing basic statistical charts using haptics [PR10].

Several tactile systems attempt to go beyond its static nature, such as using robotics [GMSK19], tangible objects [MRB10], and custom refreshable displays [PDL*08]. Another line of work attempts to automatically translate a digital graph into a tactile graphic version that works for swell papers [LIR*05], such as converting text to braille and color to textures. The automated conversion provides a promising direction for handling the accessibility of a sheer amount of visualizations created nowadays. The recent research effort in data physicalization shed some light on bringing interactivity to tactile graphics [JDI*15], although the cost of custom hardware still remains challenging to address.

Multi-sensory perception is often employed to overcome the limitations of a single modality. Figure 8 shows various multi-modal combinations. Combining verbal (speech) and non-verbal cues (sonification, tactile graphics, haptic feedback) was the most common combination (17/20). For instance, GraVVITAS provides an on-demand audio description on a touched element along with haptic feedback [GM11a] (Figure 9A). Similarly, AudioFunctions couples sonification with speech while using touch to indicate

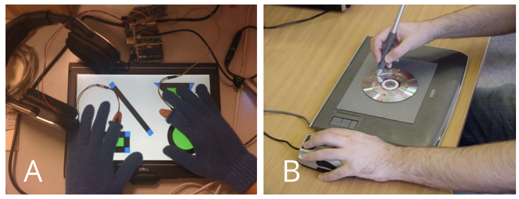


Figure 9: *Examples of multi-modal systems. (A) GraVVITAS [GM11a] using a haptic glove with audio feedback on top of a tablet tracking finger locations and (B) Tac-tiles [WB06b] using graphics tablet augmented with a tangible pie chart relief with dynamic tactile display for non-dominant hand.*

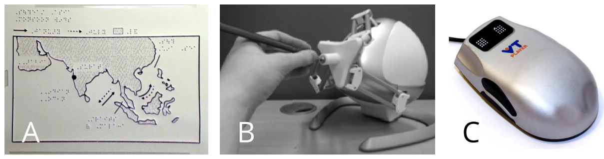


Figure 10: *Examples of conventional assistive hardware technologies. (A) swell papers [FM15]. (B) Novint Falcon haptics controller [WH14]. (C) Refreshable braille display on a mouse [WB06b]*

a point of interest in the graph [TBG*14]. On the other hand, tactile graphics were also often integrated with digital speech and sonification through custom hardware [FM15] and tangible overlays [LCC*13, WB06b] (Figure 9B). General-purpose tactile overlay systems such as IVEO [GB06] and Tactile Talking Tablet [LG01] often also used the same combination of speech and tactile graphics. A recent study demonstrated comparable performance between tactile graphics with braille and digital tablets with haptic vibration and audio feedback, highlighting an electronic version as a viable solution [HMG19], although still costly to deploy.

While most visualizations to date still focus on single-modal interaction typically using mouse and keyboard, recently multi-modal interaction is gaining interest due to the variety of personal devices available today [LCI*20]. Some latest research investigated the use of pen and touch to author visual data stories [KHRB*19] and personal visualizations [KIHR*19], as well as the combination of speech and touch to support data exploration and analysis [SS17] seamlessly. While these works were not applied in the accessibility context, multi-modal interactions show a promising research avenue to *overcome the limitation of a single accessibility modality* and provide more immersive and interactive experiences.

4.7. Assistive technology

A designer must consider both alternative sensory modalities and assistive technologies that support them (Figure 10). These two dimensions go hand in hand with each other but are distinct and merit separate considerations.

The most widely accessible technology is a screen reader (21/56) that allows users to navigate a computer screen by conveying text on the screen using either speech or braille output. Many consumer computers have screen readers freely available such as Android's Talkback, Apple's VoiceOver, Microsoft's Narrator, and NVDA and JAWs—not free. It often coordinates with input devices such as keyboards to support the navigation of content on a screen (6/56). Going beyond a simple text, several systems leverage SVG to help to navigate text descriptions for various components within a chart [EMW19, Hah15, GMS18].

Tactile devices are more costly and often priced up to tens of thousands of dollars, making them less accessible to average users. However, they tend to provide more immersive experiences of graphics. In our paper collection, haptic devices (e.g., Novint Falcon) (12/56), embossed prints (12/56), and touch-enabled tablets were commonly observed. We also observed custom hardware for novel multi-modal interactions such as using mobile robots [GMSK19] and tactile-audio devices [PDL*08], as well as refreshable braille displays (1/56).

Different assistive technologies have trade-offs. To reach a broader audience, software-based options such as screen readers and sonification software are more accessible. Most tactile devices are costly and difficult to set up but can provide a visceral and enactive experience. For a visualization to be most accessible, it *needs to be compatible with diverse technology options*. A challenge is that the assistive technologies are general-purpose, and it requires engineering and design effort to make visualizations work with these technologies. Recent studies investigate novel technologies, including a dynamic physical bar chart [TJW*16], data ediblization, and an olfactory device [PBE19, BPAE20], although not discussed in the accessibility context.

5. A Preliminary Model for Visualization Accessibility

We put together a preliminary model for visualization accessibility by synthesizing the different processes and strategies we observed from our design space analysis (Figure 11). The model's goal is to capture how visually impaired people might process a visualization and to guide the development and evaluation of accessible visualizations [Mun09]. We devised the four stages in the model based on the user's flow of accessing information. The model is similar to but different from existing models [Shn96, VHP09] (e.g., the visual information seeking mantra [Shn96]) as they focus on *visual processing*.

1. Notifying the existence of a chart is a unique need for the visually impaired. Since charts are typically embedded within various forms of information media such as news articles, the notification is an important first step for visualization accessibility. This can be done by simply mentioning "Chart" at the beginning of the alternative text or describing the type of the chart such as "Bar Chart" [CJP*19b, CJP*19a]. While this notification may be best conveyed in the speech modality, tactile graphics can mention the chart type in braille at the top left corner [EW17a].

2. Providing an overview of the chart requires succinctly communicating the summary of a chart, including its intended message, visual encoding structure, and descriptive stats (e.g., average, min/max). Having a good title can help convey the message (e.g., *"Percentage of uninsured Americans"* vs *"America's uninsured rate dips below 10%"* [BBK*15]), with a caveat that overstating the message rather than the underlying data itself can bias people toward incorrect conclusions [KLK19].

Multi-hand exploration, as well as speeded sonification, can also provide an overview of the data trends [GM11b, SJJJ19]. Conveying the encoding structure is also important to compensate for the lack of vision. Visually impaired people expect to recognize guiding elements for understanding data encoding, such as axes, tick marks, labels, and legends [EW17b]. The successful recognition of such guiding elements can help to keep a sense of orientation [EW17a], which is essential for both tactile and auditory graphs [EW17a, TBC*16]. It is preferable for legends to be placed at the top-left corner for faster discoverability [EW17a].

3. Offering details only when requested is desirable to avoid overwhelming visually impaired people as a non-visual channel's capacity is limited. Auditory perception involves slow serial processing. A brief text should be presented first as an overview and guide people to determine whether to read a long detailed description (e.g., `alt-text` and `longdesc` in HTML) [ADL*02]. To address the complexity of a prolonged text or the limitation of a simple alt text, one can leverage structured and navigable text using custom formats such as SVG or HTML [Hah15, SF18]. Similarly, for a sonified graph, individual data points can be playable based on the user's control and navigation [TBC*16].

In contrast to sound, touch can enable faster data exploration through multi-touch support [GM11a]. However, similar to sonification, the information resolution of haptic feedback and tactile graphics is low, and thus they may not be suitable for conveying accurate data values [HMG19]. The number of textures and the density of guidelines should be carefully controlled for better discriminability; they may be better removed if dispensible [EW18]. Braille labels in addition to graphics, can help the reading of precise values [EW17b]. Multi-modal interactions can enable better on-demand exploration. For instance, one can use tactile graphics to provide rapid and nonlinear access to data locations while using speech to convey precise values [FM15, WB06b, DPSS10].

4. Conveying the context when necessary and helpful might be required when users are actively exploring the details. For instance, when navigating through individual data points, it would be useful to provide contextual information such as whether there was an increase in value relative to the previous point, where the current pointer is positioned (e.g., am I at the starting point, did I reach the endpoint?), and what adjacent points to the current focus are [FLST13, CMS07]. For the tactile and haptic modalities, different levels of sounds, vibrations, and gravitational forces can be used to provide spatial context, such as delimiting the boundaries between data points, indicating going out of chart boundaries, as well as pulling the current pointer toward closest data points [DPSS10, GM11b]. The contextual cues can be given along with the details or triggered only when needed or requested. It can be beneficial for active exploration rather than passive guided presentation [DPSS10] and when navigating large and complex visualizations.

Limitations. The accessibility model focuses on the reading task and is based on our analysis of past research. It should be extended through further research to incorporate the recent progress of the visualization field.

Table 1: *The full paper collection used to construct the design space and the accessibility model.* ***Chart Type****:* `Basic`*-basic statistical charts,* `Advanced`*-networks, maps, and surfaces.* ***Contribution****: ■ Emprirical Research ■ Artifact ■ Survey ■ Methodological*

	WHY						WHAT											HOW													
	Blind	Visually Impaired	Low Vision	Sighted	Read	Create	Basic	Advanced	None	Navigate	Visualize	Annotate	Derive	Filter	Guide	Select	Coordinate	Detail	Overview	Existence	Braille	Speech	Haptic Feedback	Sonification	Tactile Graphic	Screen Reader	Embosser	Keyboard	Touchscreen Tablet	Other	Contribution
[YMB*20] Tactile Presentation of Network Data: Text, ...	■		■		■			■	■									■	■						■		■				Emprirical Research
[BCES19] An Automated Approach for the Recognition...	■				■		■		■										■					■		■					Artifact
[SJJJ19] Comparing User Performance on Parallel-Tone...		■			■		■		■									■	■			■		■		■				■	Emprirical Research
[GMSK19] RoboGraphics: Dynamic tactile graphics ...	■	■	■		■		■			■								■	■			■			■				■	■	Artifact
[LLS19] Sociotechnical Considerations for Accessible...	■				■		■		■									■	■		■				■					■	Methodological
[EMW19] SVGPlott: An accessible tool to generate...	■					■	■				■							■	■	■	■	■			■	■	■	■		■	Artifact
[HMG19] The Comprehension of STEM Graphics via...		■			■		■		■									■	■		■	■	■		■		■		■		Emprirical Research
[CJP*19b] Visualizing for the Non-Visual: Enabling...		■			■		■		■									■		■		■				■					Artifact
[EW18] A user study to evaluate...	■	■				■	■		■									■	■						■					■	Emprirical Research
[GMS18] An accessible interaction model...	■		■			■	■			■	■							■	■		■	■			■	■		■			Artifact
[WM18] Effectiveness of tactile scatter plots...	■				■		■		■									■	■						■					■	Emprirical Research
[SF18] EvoGraphs - A jQuery plugin to create...		■			■		■		■									■	■			■				■					Artifact
[KM18] Multimodal deep learning using images and text...	■	■			■		■		■										■			■				■					Artifact
[WI18] Textures suitable for tactile bar charts...		■			■		■		■												■				■					■	Emprirical Research
[EW17a] Analysis of tactile chart design	■				■		■		■									■	■						■		■				Survey
[EW17c] Improve the accessibility of tactile charts	■	■				■	■	■	■												■				■		■				Emprirical Research
[MPS17] Towards accessible graphs in HTML-based ...	■					■	■		■									■				■				■					Emprirical Research
[WAYM16] Development of tactile graph generation web...	■			■		■	■				■							■	■		■				■		■				Artifact
[TBC*16] Auditory Graphing Software in the Classroom...	■			■		■	■			■	■	■						■	■			■		■				■		■	Emprirical Research
[WOH*15] ASVG Accessible Scalable Vector Graphics...	■	■			■		■			■								■	■		■	■				■		■		■	Artifact
[ZT15b] ChartMaster: A tool for interacting with stock...		■			■		■						■	■	■	■		■				■				■					Artifact
[FM15] The tactile graphics helper: Providing audio ...	■			■	■		■	■									■	■	■	■		■			■		■			■	Artifact
[TBG*14] AudioFunctions: Eyes-free exploration of...		■				■	■				■					■		■	■			■		■					■		Artifact
[AAH14] Developing a verbal assistance system...	■		■		■		■		■										■			■	■							■	Emprirical Research
[MSMC14] Evaluating the accessibility of line graphs ...		■			■		■		■										■			■				■					Artifact
[WH14] Haptics visualisation of scientific data for visually...		■			■		■			■								■	■			■	■	■				■		■	Artifact
[BMS*14] Including blind people in computing...	■			■		■		■		■	■						■	■				■				■		■			Artifact
[LCC*13] Development and Evaluation of Two Prototypes...	■				■			■		■				■		■	■	■				■		■					■	■	Artifact
[FLST13] Evaluating a tool for improving accessibility...	■				■		■			■								■	■			■				■		■			Artifact
[GTPG13] Implementing disability accommodations...	■				■		■		■										■	■		■				■					Artifact
[GPBK12] Learning non-visual graphical information ...	■				■		■		■										■			■	■						■		Artifact
[ABP12] Non-visual presentation of graphs...		■				■	■				■								■				■							■	Artifact
[GM11b] GraVVITAS: Generic multi-touch presentation ...	■				■		■			■								■	■			■	■	■					■	■	Artifact
[KL11] Handscope: Enabling blind people to experience...	■				■			■	■										■	■			■							■	Artifact
[MRB10] Clutching at straws: Using tangible interaction...		■			■		■			■	■							■	■					■	■					■	Artifact
[CW10b] Digitizer Auditory Graph: Making graphs...		■		■	■		■		■										■					■						■	Artifact
[DPSS10] Multimodal presentation of two-dimensional...		■			■		■			■					■	■		■	■			■	■							■	Artifact
[PR10] Review of designs for haptic data visualization		■			■		■	■	■												■		■						■	■	Survey
[WM10] Universal design of auditory graphs...		■			■		■		■												■			■						■	Emprirical Research
[GMH10] Usability of accessible bar charts	■				■		■		■									■	■			■	■				■				Emprirical Research
[FBV*08] A syntactic analysis of accessibility ...	■	■			■		■		■										■			■				■					Survey
[WCCE08] Decision tree induction for identifying trends...	■				■		■		■										■							■				■	Artifact
[BMS08] Haptic and aural graphs exploration...		■			■		■			■									■			■	■	■						■	Artifact
[PDL*08] Refreshable tactile graphics applied to...		■			■		■	■		■									■			■			■				■		Artifact
[ESC*07] A browser extension for providing visually...		■			■		■		■										■			■				■					Artifact
[CMS07] Teaching graphs to visually impaired students ...	■				■			■		■								■	■			■		■		■			■		Artifact
[WB06a] Feeling what you hear: Tactile feedback for...	■	■			■		■			■	■							■	■			■			■	■			■		Artifact
[KB06] Non-visual overviews of complex data sets	■	■			■		■			■									■					■	■				■		Artifact
[WB06b] Tac-tiles: Multimodal pie charts...		■			■		■			■								■	■			■		■	■				■		Artifact
[LIR*05] Automating tactile graphics translation	■				■		■				■								■						■		■				Artifact
[BSP04] Issues in the non-visual presentation...		■			■			■	■										■			■		■		■					Survey
[ADL*02] Evaluation of long descriptions of statistical...	■		■		■		■	■	■										■			■				■					Emprirical Research
[YB02] Multimodal Virtual Reality versus Printed Medium...		■				■	■			■	■							■	■			■	■	■						■	Artifact
[YRB01] Haptic graphs for blind computer users	■				■		■			■								■	■				■							■	Artifact
[RYB*00] Constructing sonified haptic line graphs...	■				■		■			■	■							■	■				■	■						■	Artifact
[FB99] Design of a haptic data visualization system ...		■			■		■			■	■							■	■			■	■							■	Artifact

Figure 11: *A preliminary model for accessible visualization design, following a* ***user's flow of processing information****. It starts with notifying the user that there* ***exists*** *a chart at the current location of interest. It can then convey the* ***overview*** *of the chart, including the intended message and its structure and orientation. The* ***details*** *such as individual data points can be presented only when requested to avoid overwhelming the user. Multi-modal interaction may work best for accessing details, such as touching a point to activate speech with more information. While navigating the details, the model might offer* ***context*** *information such as neighborhood data and the surrounding environment.*

6. Opportunities and Challenges

Below, we discuss unexplored opportunities and future challenges based on the lessons learned from building the design space and findings from collected publications.

6.1. Diverse users, visualizations, and interactions

Developing design principles to leverage remaining vision: Most research in our collection did not consider various types of visual impairment. Among those who have visual impairments, only around 15% are blind. The rest with low vision still extensively leverage their residual vision [Wor10]. One study echoes this necessity by showing the difference between totally blind and partially sighted participants in terms of describing a line chart and detecting line segments [AAH14]. How can we personalize assistive technology based on the different characteristics of visual impairment? How can we leverage the remaining vision for maximizing information gain? Additional visual aids such as magnification and contrast enhancement can be more beneficial than exclusively relying on non-visual aids. Traditionally underused visual channels such as flickering, motion, depth cues, and glow can be useful and worth investigating, as well as quantifying differences between non-visual and visual aids.

Characterizing the role and responsibility for sighted teachers: Another neglected user group is sighted people who frequently are in a position of collaborating with visually impaired users. While little research in our collections includes sighted teachers in their study, their role remains rather passive as someone who would provide supplemental feedback on the research [BR15, FM15, TBC*16]. Systematic investigations will be required on the roles of sighted users in involving the process of improving visualization accessibility. For example, given the importance of early education in visualization literacy [ARC*17], what would be the ideal pedagogical set-up for instructors to teach early age visually impaired students about how to read and create visualizations?

Building knowledge beyond simple visualization: A plethora of advanced visualizations such as treemaps and parallel coordinates, and complex interactions involving selections and linked views are currently out of scope for visualization accessibility research. We first need to map out a detailed picture of how advanced visualization techniques differ from simple ones along the accessibility aspect and what additional support would be necessary. A good starting point would be leveraging existing visualization and interaction taxonomy (e.g., [Chi00, YaKSJ07]).

Developing accessible pipelines to create visualization: Another imbalance we observed is that existing research mostly supports visualization reading tasks (44/56) as opposed to creating tasks. Creating visualizations is equally important to close the loop on visualization literacy. In fact, participants in a study expressed they do want to create visualizations [EW17a]. Accessible interfaces and methods of creating visualizations can empower visually impaired people to be active producers rather than passive consumers. Research questions are then what exact needs exist for creating visualizations. What can we learn from the existing accessible authoring tools that support creating activity (e.g., writing tool, drawing)? Can we support the authoring of more advanced exploratory and explanatory visualizations?

6.2. Toward generalizable and affordable methods

Automating the process of making visualizations accessible: Current methods for ensuring visualization accessibility are mostly fragmented by different chart types. A scalable method will be ideal for dealing with the sheer number of interactive visualizations flooding in on the web. A few early approaches presented an automatic generation of chart descriptions [GMS18, WOH*15]. Existing charting libraries such as HighCharts [hig] and Vega also provide similar options. These automatic and general approaches are crucial for supporting interactive visualizations where views are constantly changing but are currently at the preliminary stage.

Leveraging low-cost and commonly available mediums: As specialized assistive devices (e.g., refreshable braille display) can be costly, future research should navigate more universally affordable solutions. For example, natural language generation can be an inexpensive alternative by producing chart descriptions of different information granularity (e.g., insight generation [LES20, CBYE19, SDES19]). Likewise, question & answering could be a great alternative to avoid navigating numerous data points by simply asking a query [KHA20]. Investigating ways to make use of multimodal interactions in commonly available smartphones and tablets is also a promising direction [SLHR*20].

6.3. Bridging knowledge between different sensory perceptions

Expanding on the established visual perception framework: Few works leverage the existing knowledge framework about sensory perception in supporting accessible visualizations. While visual perception has been at the forefront of most endeavors, some of the systematic approaches the community has embraced can be applied to understanding other modalities. For example, when designing auditory visualizations, researchers can classify, characterize, and evaluate the different auditory channels by drawing parallel effectiveness and expressiveness principles.

Investigating the trade-off of multiple modalities: A majority of the existing work focuses on a single modality. While it is useful to analyze each sensory modality's specificity, understanding the trade-off among multiple related modalities in creating and reading visualizations is critical to enhancing accessibility. For example, conducting comparative studies that identify contexts and tasks that one modality outperforms another can be informative.

7. Conclusion

In this work, we analyzed research papers on visualization accessibility over the last two decades. We derived a design space of accessible visualizations including the target users, tasks, the assistive technologies, and visualization design. Based on the review of the papers, we propose a model to support accessibility in visualizations. We outline the opportunities and challenges to inform future research in the domain. We believe that our effort paves the way to initiate more active work to support a broader audience in visualization research.

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