How Do Low-Vision Individuals Experience Information Visualization?

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ABSTRACT

In recent years, there has been a growing interest in enhancing the accessibility of visualizations for people with visual impairments. While much of the research has focused on improving accessibility for screen reader users, the specific needs of people with remaining vision (i.e., low-vision individuals) have been largely unaddressed. To bridge this gap, we conducted a qualitative study that provides insights into how low-vision individuals experience visualizations. We found that participants utilized various strategies to examine visualizations using the screen magnifiers and also observed that the default zoom level participants use for general purposes may not be optimal for reading visualizations. We identified that participants relied on their prior knowledge and memory to minimize the traversing cost when examining visualization. Based on the findings, we motivate a personalized tool to accommodate varying visual conditions of low-vision individuals and derive the design goals and features of the tool.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in visualization**; **Visualization design and evaluation methods**; **Accessibility**.

KEYWORDS

data accessibility, visualization accessibility, low-vision, people with visual impairments

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1 INTRODUCTION

Visualization accessibility has been gaining momentum in recent years, driven by a growing research community's interest in ensuring equitable access to data for people with visual impairments. However, recent research [45] reveals a significant oversight in low-vision individuals (LVIs) who can use their remaining vision to interact with the world. According to statistics in 2017, around 6 million Americans had low vision (despite best corrective measures), and around 1 million had blindness [34]. Beyond genetic disorders, age-related macular degeneration (AMD) stands out as the major cause of low vision [48], implying the relevance of the issue to everyone.

Unlike non-sighted individuals who solely rely on screen readers to read out information, LVIs use various assistive technologies that aid visual inspection [62]. For example, LVIs use screen magnifiers that enlarge on-screen contents to make them more readable, or screen color filters that adjust the color and contrast of the contents to suit their needs.

In conjunction with technology use, the individuals' visual conditions may impact how they interact with visualizations. Consider a scenario where a viewer, characterized by low contrast sensitivity and tunnel vision, utilizes a screen magnifier to examine a visualization. In this scenario, how would the viewer examine the visualizations? What challenges would they encounter, and what types of support are necessary for them to access the same level of information as fully sighted individuals? These questions have not been explored, but they are crucial for enhancing the accessibility of visualizations for individuals with low vision.

To bridge the gap in knowledge and support, we set out to investigate how LVIs experience visualizations. We conducted a contextual inquiry with low-vision participants by situating them with real-world visualization stimuli. The participants were encouraged to freely navigate several visualizations with assistive technologies they usually use and perform analytical tasks. Through thematic analysis using recorded and transcribed study sessions, we analyzed their verbal and behavioral responses to understand how LVIs read and comprehend visualizations.

While participants shared that the default zoom level for the general purpose might not be optimal for reading visualization, we observed that all participants used a screen magnifier to examine visualization stimuli. We also found that the tasks required to construct an overview of visualizations were challenging as participants needed to synthesize sequentially examined partial views. Participants utilized various strategies to examine visualizations using the screen magnifiers, such as relying on their prior knowledge and memory to minimize the traversing cost when examining visualization.

Our contribution is three-fold:

- We demonstrated how low-vision participants navigate visualizations with the assistance of assistive technologies and identified the challenges they faced and the strategies they

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employed to overcome these challenges while interacting with visualizations.
- We contextualized our findings with Web Content Accessibility Guidelines (WCAG) to empirically validate them, discuss connections between our findings and established design practices, and call for improvements in practice.
- We motivate a personalized tool based on our observations and derive design goals and features for such a tool from the study findings.

2 RELATED WORK

2.1 Making Visualization Accessible

Many prior work focus on improving accessibility for blind and low-vision individuals who rely on screen readers as their primary tool for information access [43, 44, 54, 56, 57, 67]. One basic but essential way to make visualization accessible is to provide alternative text [32, 33, 36, 40, 49, 50, 55]. Examples include EvoGraphs, SIGHT [28], and guidelines for alternative text formulation [40]. A conceptual model of illustrating visualizations and their patterns and insights has also been developed to support formulating better visualization descriptions for visually impaired individuals [49]. Beyond alternative texts, several works investigate how to make visualization navigable to screen reader users [24, 64, 69]. For example, Olli [24] is an open-source library that restructures visualization specifications as a tree structure, enabling comprehensive exploration of visualization with screen readers.

2.2 Accessibility for Low-Vision Individuals

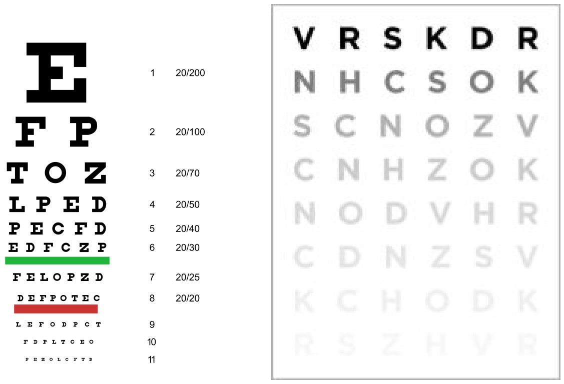
While research has been conducted on visualizations for individuals with color vision deficiencies [16], there remains a gap for other forms of low vision. The accessibility community in general has investigated how to improve accessibility for the low-vision population. Since 1998, Jacko and Sears have emphasized the importance of designing systems to support partially sighted computer users [38]. Cimarolli et al. [29] conducted research exploring the challenges faced by people with vision loss and how it could change over time, especially for older adults with progressive vision loss. They summarized functional, social, and psychological challenges that LVIs could encounter and derived implications for rehabilitation. Szpiro et al. [61] conducted a study to understand the challenges and strategies that low-vision participants may encounter in wayfinding and grocery-shopping tasks, finding that, despite the challenges, LVIs still try to take advantage of their vision.

Previous research has also explored the challenges LVIs encounter when using assistive technologies. Theofanos et al. [63] found that magnification could cause participants to miss important information and context. Szpiro et al. [62] further investigated a similar question using computers and smartphones, finding that current accessibility tools could not provide efficient enough support to read content due to the lack of enough control and difficult interaction. To overcome the challenges, many tools [22, 23] have been developed, such as Navisio [22] and approaches that support cursor use [35, 46].

With the continuous development of technology, Virtual Reality (VR) has become an important part of assistive technology. For example, Zhao et al. [68] investigated the visual experiences of LVIs when using different vision enhancements for various viewing tasks and designed vision enhancement systems using head-mounted displays.

3 BACKGROUND: CHARACTERIZATION OF LOW VISION CONDITION

Low vision is a visual condition that cannot be corrected using glasses, contact lenses, or standard treatments like medicine or surgery [6]. Generally, legal blindness is defined as a best-corrected visual acuity worse than 20/200 (the person needs to be at least 20 feet away to see some objects that a person with "normal" vision can see from 200 feet away). Contrary, low vision diagnosis requires a best-corrected visual acuity of less than 20/40 in the better-seeing eye, excluding those classified as blind by the U.S. Centers for Disease Control and Prevention [2]. Low vision can result from congenital visual impairments, age-related macular degeneration, cataracts, diabetic retinopathy, glaucoma, or physical injuries to eyes [53]. In this section, we outlined five visual functions that characterize low vision, inspired by the structure presented in WCAG [3]. Additionally, we synthesized relevant works to describe 1) the definition of the visual function, 2) test methods, 3) symptoms, 4) the possible impact on visualization reading, 5) the availability of assistive technologies, and 6) known coping strategies from a viewer's end.



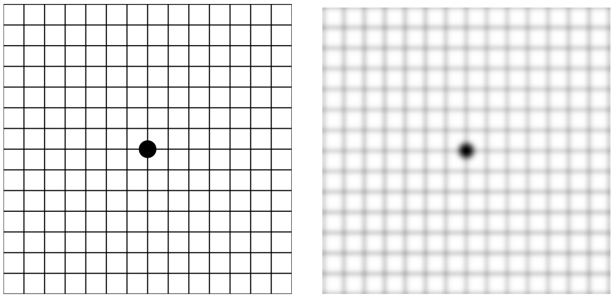
(a) (b)

Figure 1: The Snellen chart (a) [13] to test visual acuity and the Pelli-Robson chart (b) [21] to test contrast sensitivity.

3.1 Visual Acuity

Definition: Visual acuity is a measure of the clarity of vision and refers to how well a person can see details and distinguish objects [19]. It is commonly assessed by determining the smallest letters or symbols that a person can recognize on a standardized eye chart. Visual acuity is a key criterion used to determine whether a person is legally blind or not.

Test methods: The Snellen chart [58] (Fig. 1(a)) is the most widely used test for visual acuity assessment. It measures a person's ability to recognize progressively smaller letters or symbols at a specified distance.



(a) None blurred vision [10]
(b) Blurred vision/Hazy vision

Figure 2: Illustrations of blurred visions compared to none-blurred vision.

Symptoms: Two types of visual phenomena are associated with low visual acuity. The first type is *blurred vision*, where the viewer experiences a loss of focus when looking at objects that are either near or far away. The second type is *hazy vision*, where the viewer experiences the sensation of looking through a fog or haze. Both of these types of visual phenomena can cause objects to appear unclear or fuzzy (as shown in Figure 2(b)). However, in the case of blurred vision, viewers may be able to adjust their focus and see things more clearly through the use of corrective glasses or even by squinting their eyes. With hazy vision, neither of these approaches helps the viewer see more sharply.

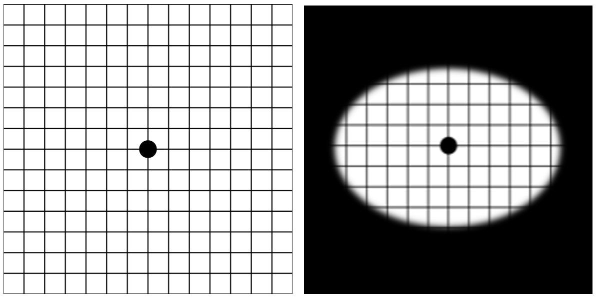
Influence in reading visualization: Extreme low visual acuity, such as 20/200, can prevent a viewer from reading content with small font sizes or narrow spacing because their ability to distinguish small details is significantly reduced. The text in legends, labels, or marks on the visualization may appear too small and indistinguishable, making it difficult or impossible for the viewer to read.

Assistive technologies: While wearing glasses or contacts can improve visual acuity, most low-vision individuals still require additional assistance. The screen reader reads texts and the screen magnifier allows viewers to adjust the contents large enough for them to read. Content generators or ad-hoc applications developed specifically to alleviate this challenge [37] can also increase the line space, word space, and font size and choose the appropriate font style to make the content more accessible.

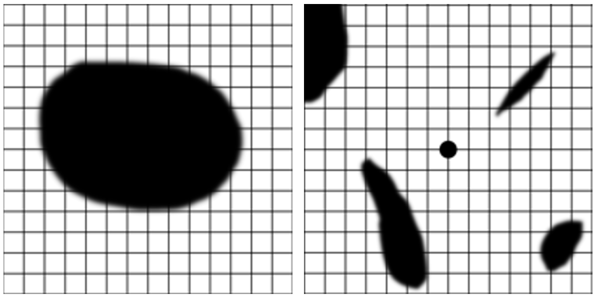
Viewers' coping strategies: Viewers can adjust their distance, like moving closer to the monitor to see things clearer [62]. While it may be detrimental to their vision health, another common approach for alleviating blurred vision is squinting their eyes to adjust the focus.

3.2 Light Sensitivity

Definition: Light sensitivity, also known as photophobia, describes a condition that makes a person shield their eyes from light to prevent eye pain. Light sensitivity can be attributed to many reasons, from simple eye strain or dry eyes to eye infections (e.g., bacterial keratitis, uveitis), eye injuries, or eye structure problems (e.g., trichiasis). It can also be a symptom of allergies, or brain or nervous system disorders (e.g., migraine) [4, 8].



(a) Amsler Grid [10]
(b) Tunnel Vision



(c) Central visual field loss
(d) Other visual field loss

Figure 3: Illustrations of different types of visual field loss.

Test methods: In the past, assessing light sensitivity depended on the use of questionnaires (e.g., "How often do you experience headache upon exposure to bright or artificial light"). However, a new instrument called the Ocular Photosensitivity Analyzer (OPA) has been introduced to measure the visual photosensitivity thresholds (VPT) more accurately [66]. This instrument generates light stimuli of different intensities using unequal ascending and descending steps, resulting in precise VPT measurements.

Symptoms: There are two different types of light sensitivity based on the severity [47]. A *true photophobia* means that eye pain can occur because of exposure to light. Under these circumstances, even moonlight is intolerable, or the bright light of a lamp with a closed lid may cause distress. On the other hand, a *so-called photophobia* is an uncomfortable vision resulting from the lack of adaptation to the diffusion of light through the ocular media. Possible symptoms of light sensitivity include difficulty opening the eye, eye discharge, redness, or eye pain.

Influence in reading visualizations: The bright colors used in visualizations, especially on the white background, can make it difficult or impossible for people with light sensitivity to read or even cause pain.

Assistive technologies: "Dark mode," will change the content from using bright colors (e.g., white background) to dark colors (e.g., black background). Simply reducing monitor lightness can help. Tinted spectacles can also alleviate pain for people with photophobia and make content more readable [41].

3.3 Contrast Sensitivity

Definition: Contrast sensitivity is a critical aspect of visual function that helps people distinguish objects from their backgrounds and perceive details in low-contrast scenes. Contrast sensitivity often results from aging, eye diseases such as cataracts or glaucoma, and certain medications [42].

Test methods: Contrast sensitivity measures the amount of contrast that a person requires to see a target [51]. The most widely used contrast sensitivity test uses the Pelli-Robson chart [31] as Figure 1(b) shows. The usage of the Pelli-Robson chart is similar to the Snellen chart, but instead of the letters having a decreasing size on each successive line, the letters in the Pelli-Robson chart have a decreasing contrast (relative to the background) on each line.

Symptom: People with low contrast sensitivity have difficulty perceiving the difference between the light and dark areas of an image, making it challenging to distinguish content from the background without sufficient contrast [42].

Influence in reading visualization: Insufficient contrast can pose challenges for individuals with low contrast sensitivity, impacting various aspects of visualizations. For instance, discerning gray text on a white background is considered to be difficult for such individuals [3]. This issue can manifest in numerous visualization elements, including deciphering gray text in legends or labels against a white backdrop or interpreting white text within gray bars in a bar chart.

Assistive technologies: Some systems offer a "high contrast" mode which can enhance the visibility of content on the screen. Since white text on a black background stands out more than text on a white background [1], some people with low contrast sensitivity use an "inverted color filter" to invert the color schema. Some existing tools in VR provide functions like edge enhancement and contour highlighting to support people with low contrast sensitivity to the target object (e.g., [68]).

3.4 Field of View

Definition: The field of view, or visual field, refers to the extent of the area that can be observed when the eye is looking straight ahead, including what can be seen with peripheral vision [11].

Test methods: A commonly used tool for assessing the field of vision is the Amsler Grid (Figure 3(a)). Individuals are instructed to hold a printed grid at a comfortable reading distance, fixate on the central spot of the grid, and report any missing or distorted areas they observe in the grid [27].

Symptoms: A limited field of view or visual field is referred to as visual field loss. Visual field loss can be categorized into three types.

(1) Peripheral field loss: also known as tunnel vision, is characterized by the loss of vision in the outer edges of the visual field, leaving only the central portion visible (Fig. 3(b)).

(2) Central field loss: the vision is reduced or absent in the middle of the visual field (Fig. 3(c)).

(3) Other field loss: individuals may have spots in their visual field (Fig. 3(d)).

Influence in reading visualization: With visual field loss, viewers may miss content without knowing that they missed it [62]. In addition, comparing values between marks can be hard as their limited field of view can interfere with the task.

Assistive technologies: Existing approaches try to scale the content to a small range (e.g., rewrap for one-direction scrolling, reflow to a single column, adjust line length [3]) to increase the chance that the viewers can see all the contents regardless of their view loss.

Viewers' coping strategies: Viewers can adjust their behaviors [53]. For instance, if they experience central field loss, they can use their peripheral vision to look at the target. Additionally, they can check the content repeatedly to ensure that they read all the information correctly [62].

3.5 Color Vision

Definition: Color vision refers to the ability to distinguish differences between light composed of various wavelengths regardless of their intensity [5].

Test methods: A widely used method for testing color vision is the Ishihara color blindness test, which primarily focuses on assessing red-green color blindness. Blue-yellow color blindness and complete color blindness are rare conditions. The test involves presenting a sequence of plates, each comprising a circle of colored dots with a number or shape concealed within the pattern. Individuals with full-color vision can effortlessly recognize the number or shape, while those with color vision deficiencies find it challenging to see the concealed pattern.

Symptom: There are three types of color blindness, including Deuteranopia (red-green blindness, missing L-cones), Tritanopia (blue-yellow blindness, missing S-cones), and Achromatopsia (monochromatic vision, complete color blindness, missing all types of cones) [20]. Missing M-cones does not cause color blindness but color weakness.

Influence in reading visualization: Viewers with color blindness will perform worse in search tasks when colors that are hard for them to distinguish are used to organize information or used as the primary attribute of the target [39].

Assistive technologies: There are various tools available, such as the digital color meter, that can detect colors displayed on a screen and provide the corresponding numerical value to "read" the color. Such tools can be beneficial for individuals with color blindness, allowing them to identify the colors they are viewing or, at the very least, become aware of when a color changes. Moreover, a variety of color filters are now available to modify the color on the screen to accommodate different forms of color blindness [18].

Viewers' coping strategies: People with color vision deficiencies mostly rely on the brightness/darkness of the color to distinguish the target in an image.

4 HOW LOW VISION PEOPLE EXPERIENCE VISUALIZATION?

We conducted a contextual inquiry where participants were situated with visualization reading scenarios and asked questions related to their interactions. Specifically, we aimed to understand their usage of assistive technologies and the challenges they encountered while reading and comprehending visualization.

P Number	Gender	Legally Blind	Visual Acuity	Field of View	Light Sensitivity	Color Blindness
P1	M	Y	20/200	Full	Y	Y
P2	M	Y	Unknown	Some spot loss	N	Y
P3	M	Y	20/400	Central vision loss	N	N
P4	M	Y	20/200	45 degrees	Y	N
P5	F	Y	20/800	Central vision loss	Y	N
P6	M	Y	20/400	20 degrees & central vision loss	Y	Y
P7	F	Y	20/500	<10 degree	Y	N
P8	F	Y	10/400	Nearly full	Y	Y
P9	M	Y	20/500	Central vision loss	Y	Y
P10	M	Y	20/600	Full for one sight (one eyesight loss)	N	N
P11	M	Y	20/150	2 degrees	Y	N

Table 1: The demographic information and vision conditions of participants.

4.1 Participants

We recruited participants through mailing lists of organizations serving blind and low-vision communities. The recruitment criteria consisted of legally blind low-vision adults with *remaining functional vision* who use assistive technologies like magnifiers or screen readers daily. We randomly selected a participant at a time from the initial pool of 48 survey respondents to reach out until the findings were saturated. After interviewing 11 participants, we observed repetitive themes in participants' behaviors and no new insights toward our research questions. Thus, we stopped the recruitment. This process resulted in interviewing 11 respondents (3 females and 8 males, self-identified), and their ages ranged from 25 to 78 years (M = 51.9, SD = 17.51). The interviews were conducted via Zoom and lasted an average of around 70 minutes (M = 72.4 mins, SD = 8.81 mins). Participants received a $25 gift card as a token of appreciation. More information about participants is in Table 1.

4.2 Study Stimuli

To situate participants with the real-world scenario, we prepared visualization from the wild. We sourced the visualizations from online news outlets (e.g., www.nytimes.com) and government websites (e.g., www.usa.gov) to create realistic scenarios. We vary the topic and visualization types (bar, pie, line, and scatterplot/bubble chart), choosing 12 visualizations (three per visualization type). Each participant reviewed randomly selected three visualizations from different visualization types, as we aimed to limit the interview duration to approximately an hour to mitigate participants' fatigue.

4.3 Procedure

Figure 4 illustrates the overall procedure of the study. The study started by asking for demographic information (e.g., age, occupation) and other relevant information, such as their visual conditions and prior experience with assistive technologies and visualizations. Then, we explained the structure of the study, where participants were asked to examine three visualizations and instructed to "think aloud" while navigating the visualizations. Participants examined one visualization at a time. We first showed a description of each visualization and asked what they would want to do with the visualization. After that, we instructed participants to freely navigate visualizations with their commonly used assistive tools. Once participants were done, we asked them to conduct analytical tasks we prepared. We devised the tasks based on prior work from Amar et al. [15] to surface the challenges that emerged while conducting analytical tasks. Example tasks include retrieving values (e.g., how much do residential buildings cost?), determining range (e.g., what is the range of days that it takes for a Supreme Court justice to be confirmed?), etc. Each participant completed three tasks per visualization, followed by questions on their approach and how assistive technologies could have enhanced efficiency. After examining all the visualizations, participants were asked about their experiences during the navigation: what information they most focused on, the challenges they faced, and the usefulness and limitations of assistive technologies they were using. Participants were also encouraged to share their ideas on ideal assistive technologies to read visualization. The study was conducted via Zoom for two main reasons: firstly, to observe participants' behaviors in their own physical environments, such as on their personal monitors, and in their digital environments, including the use of assistive applications; secondly, to extend our reach to participants beyond our local area.

4.4 Analysis

All sessions were recorded and transcribed. We performed a thematic analysis to identify common themes and patterns within the data [26]. To develop the initial codebook, two researchers coded the transcripts of three participants independently. We then examined and summarized the codes, resulting in 17 high-level themes and 170 codes. All transcripts (including the initial three) were coded, and we revised the codes and themes in the initial codebook to achieve more accurate characterizations of quotes [26]. The final codebook and corresponding quotes were reviewed and adjusted as necessary. The final codebook comprises 15 high-level themes and 215 codes (available in the supplemental material).

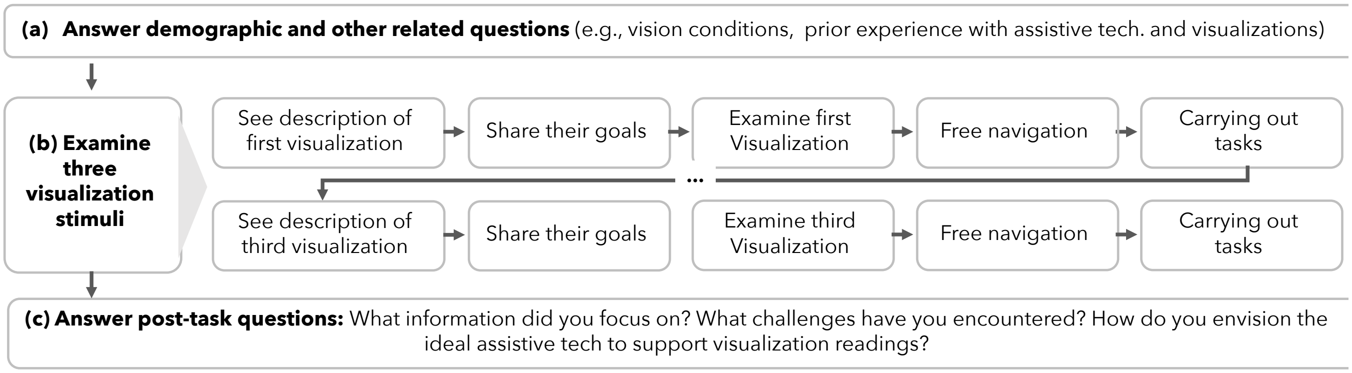


Figure 4: The study procedure.

4.5 Results

4.5.1 Visual Conditions of Participants. Participants had varying visual conditions. The visual acuity varied from 20/200 to 20/800. While a few participants (P1, P9) shared that they have a nearly full field of view, others reported that their field of view is limited. Four (P3, P5, P6, P9) reported that they had central vision loss. P2 shared that he had some blind spots. P7 and P11 had less than 10 degrees of field of view. Eight participants (P1, P4-P9, P11) reported that they had light sensitivity and five participants (P1, P2, P6, P8, P9) reported having color blindness.

Some participants had a hard time illustrating their visual conditions accurately. For example, P2 said, "I have not gotten good measurements of my vision, to be honest" when we asked about their visual acuity and the field of view. Since there are several measures to remember to characterize vision conditions and left and right sight can differ in those measures, several participants cannot recall exact measures. For example, P4 said, "It's [20/]200 in my better, and my worst is like 20/600, 800 or something."

4.5.2 Uses of Assistive Technologies. All participants used screen magnifiers or zoom-in features daily, and six participants (P2, P3, P5, P6, P9, P11) also indicated that they used screen readers. Three participants (P4, P5, P9) indicated that they used large monitors (65, 42, and 45 inches, respectively). P9 shared that he used a curved monitor, which improved the usage of peripheral vision. Moreover, three participants (P1, P6, P7) used color filters to assist with color blindness and low contrast sensitivity.

The majority of the participants (P1, P2, P3, P5, P7, P8, P11) expressed satisfaction with their current assistive tools. For instance, P7 felt the magnification feature was "working well," and P11 also appreciated the effectiveness of the screen magnifier as it allows faster reading. However, some participants reported issues with their assistive technologies. P6 combined multiple technologies to compensate for each tool's limitations. P10 shared the inconsistent performance of the tool: "There's a technical glitch. The screen reader works for a while, and then it doesn't work again, and for some types of texts, it will not [work]."

Around half of the participants (P2, P3, P4, P7, P9, P11) mentioned that they had read alternative texts for visualizations. They found them useful for understanding charts, but some mentioned their sporadic availability. For example, P3 mentioned, "I have a screen reader add-on on the browsers that I use sometimes. They're hit or miss depending on who creates the graph." P4 shared that he did not use screen readers, but he read alternative texts through the screen magnifier: "Usually, it'll come up when I put a focus on the graphic, but zoom text can be a little squirrelly so have to do that multiple times."

4.5.3 Goals of Reading Visualizations. Before presenting each visualization, we provided a brief description of the visualization and participants about their intended use. The majority of the responses were analytical tasks they wished to carry out. When we classified their responses using the low-level task taxonomy by Amar et al. [15], *finding correlation* was the most commonly mentioned goal. For example, P8 shared that he wished to know "what was the fluctuation in oil price [over time]." P7 was also curious about the correlation between two variables (hospitalization and time) illustrated in the description: "The percent of COVID, how has that been affected by the injection? Has it increased or decreased?" *Identifying extreme values* was the second most common goal participants mentioned. For example, P1 wanted to know "what religion has the highest proportion among Republicans."

4.5.4 Strategies and Preferences to Explore Visualization.

Constructing Overview as First Action. Many participants began by seeking an "overview" of the visualization. Some wanted to assess the boundary of the visualization first. For example, since P5's screen was zoomed in, the visualization didn't fit in a view. P5 stated that "initially, what I would do is I would do a quick go over so I have it up on my screen, and I would scroll all the way to the bottom, so I could see every single thing that was on the page now." P4 specifically demonstrated how he constructed an overview of the entire page. P4 mentioned, "I go around basically the whole edge of this, and I look at it in this case in quadrants. So I divided up mentally in the upper left, upper right, lower right, and lower left quadrants going clockwise." P1 also stated that he missed many elements on the screen in his previous experience and emphasized the importance of becoming aware of all the elements before focusing on one element: "We have to first look at the table on top and then look for any additional information, so I see there are these two lines." P4 echoed the sentiment of the necessity of getting the overview: "From the macroscopic view, I'm trying to establish

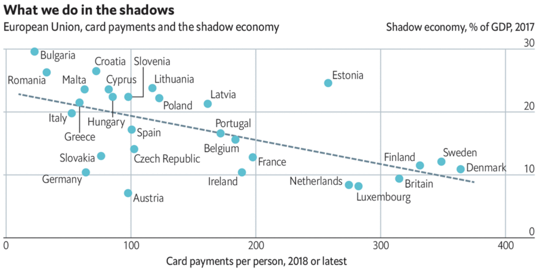


Figure 5: The scatterplot depicting the trend between card payments and the percentage of the shadow economy.

(a) (b)

Figure 6: (a) The original visualization, (b) a zoomed-in view when participants attempt to read text.

visual parameters for the extent. And for any evident trend and what I’m seeing that way, I can create a macroscopic visualization in my mind about how this thing looks.” Some participants examined visualization by counting how many elements were there to ensure they were aware of all the elements presented around the visualization. For example, P6 shared that “One, two, three, four, five, yeah, there are five elements.”

While participants attempted to construct an overview, many recognized that they could not create a good one. P6 was aware that his search is not always thorough: “It’s just that sometimes when you magnify like I did, I missed out the bottom left-hand corner.” Several participants wanted to see the overview of the visualizations specifically, but it was not easy. For example, as P7 shared, “It’s a struggle because I’m using a magnifier, so I can only see a small portion of the chart at a time.” Several participants wished for a smaller size of the visualization so that they could see the entire chart at once. For example, P1 mentioned, “I just said to my specific needs, so a little bit smaller image is actually an advantage.”

Relying on Memory and Prior Knowledge to Understand Visualization. Many participants shared that they tried to remember information to save navigation time. Either using magnifiers or zoom-in features, traversing to the information that was far from where participants were looking at cost them effort and time. For example, the legend was one of the most frequent elements that participants stared at to memorize. For example, P1 shared that “[I need to] memorize what number each one of these lines is. So that I don’t have to keep going back and forth between looking at the lines and numbers and then back to the lines.” P4 also mentioned that he constructed memory for a smoother experience. “Especially in a situation like this, where I can’t see the legend. So what I actually am doing is I’m memorizing all the information that I’m acquiring and I’m constructing a mental map or image of what is going on here.” Some participants tried to remember the patterns of the visualizations to use them later. For instance, P3 found the maximum value by recalling where the highest value was located and shared that “So I depend a lot on memory. If I’m looking at something you’re asking me like, who is the highest, we’re looking here, and then I have to scroll down and remember how much it was.”

Since participants could not skim all the data points quickly, they took a long time to *locate a data point of interest*, especially with scatterplots. They strategized their searches, often relying on prior knowledge. For example, consider the instance when P7 aimed to discern the indoor activity level of the museum from a scatterplot illustrating the correlation between contact levels and indoor activity during COVID-19 (Fig. 6(a)). P7 attempted to guess the museum’s location on the x-axis (i.e., whether the museum had low or high contact levels) and then explored the area corresponding to this judgment. P6 also exhibited similar behaviors when he examined the scatterplot that represents the relationship between card payments per person and the shadow economy (Fig. 5). He wanted to locate France but couldn’t do it easily: “It took me a while to find France. I had to think about France’s shadow economy compared to Spain [where he zoomed in] to decide where to go.”

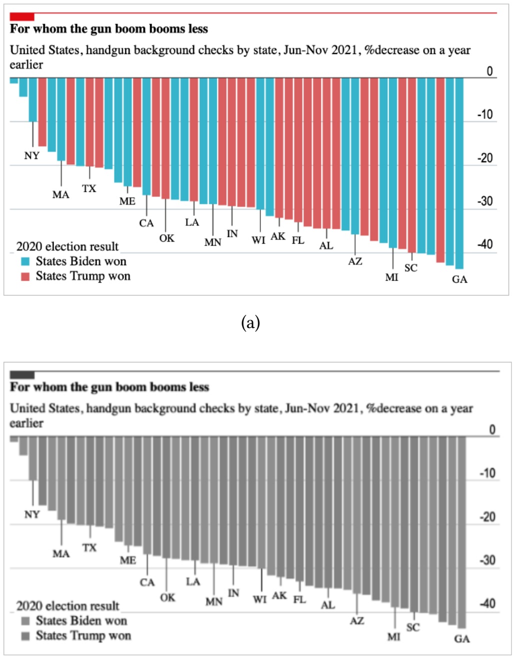
A few participants had to infer the mapping between color and the data based on their prior knowledge. P8 could not tell what colors were being used when she explored a bar chart depicting how much handgun background checks decreased compared to a year earlier by state (Fig 7(a)). While the participant was unable to distinguish the colors representing the 2020 presidential election results (i.e., blue or red), she could discern one color as being darker than the other (Fig 7(b)). The legend’s small size made it challenging to determine whether the darker color indicated a win for Biden or Trump. Consequently, she relied on her prior knowledge to associate the election results with the color intensity. She deduced, "So New York, that’s a Biden. At the end, Georgia, right, Biden. So the light color belongs to Biden."

4.5.5 *Challenges Related to Assistive Technologies.*

Some challenges in reading visualizations occurred due to the assistive technologies the participants were using.

Color Inversion Software. Participants used various kinds of inversion software operated at the OS or browser level to address for their light sensitivity, contrast sensitivity, and color blindness. For example, P3 shared, “I have found that the Firefox dark theater extension usually gets a superior result for my needs, but I do have software available on the computer.” Some participants utilize multiple color inversion tools at the same time to warrant the inverted outcome. For example, P4 utilized multiple plug-ins that had different functionalities. When the legend did not show up properly (Fig. 8(b)), he turned one filter off to make the color in the legend show up (Fig. 8(c)).

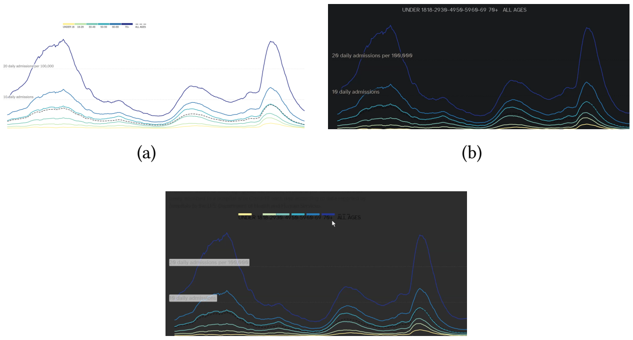
The inversion results do not always deliver the preferred result or provide coherent results across participants. For example, with the P9’s set-up, the bar chart did not invert correctly as he expected



(a)

(b)

Figure 7: (a) The original visualization, (b) simulated result given P8's condition.



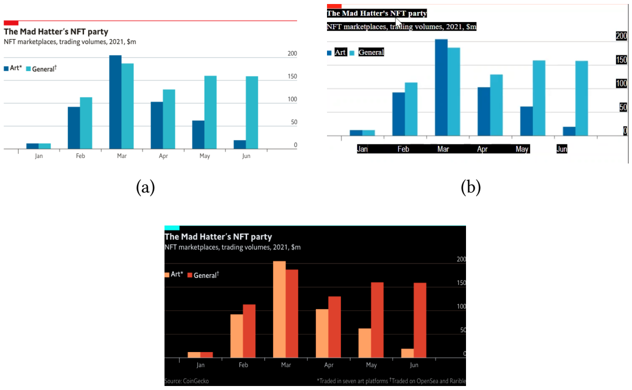
(a)

(b)

(c)

Figure 8: (a) The original visualization, (b) and (c) two variations of the inverted version of the visualization.

(Fig. 9(b)). As P9 stated, "I didn't have the advantage of having inverted colors because the charts came across to me in a very light gray. With a light background, which for a visually impaired person is perhaps one of the hardest backgrounds to read on." However, some software used by another participant was able to invert the background (Fig. 9(c)) while also changing the color of the bars.



(a)

(b)

(c)

Figure 9: (a) The original visualization, (b) and (c) two variations of the inverted version of the visualization.

The Default Zoom Level. The default zoom level of the magnifier that participants used, in general, was not always optimal for examining visualizations. For example, P7 shared "My magnifier wasn't large enough to cover the entire screen, so I wasn't sure if I had already counted [the marks]. So, I got a little confused. Perhaps my magnifier needed to be larger, or the chart needed to be a little smaller." Also, within a visualization, different tasks may require different levels of zoom. For example, P7 explored a small annotated text and a thin line associated with the text; she shared the need for easy configuration for zoom level: "Enlarging the magnifier without having to go back into my accessibility [setting], increasing it from 300% to 500%, just by using either the touch or a keystroke, I would love that." P5 hoped to have different zoom levels across different chart types: "[I wish] it would be on a greater magnification of the bar chart. So it'd be easier to see how close it is to five or ten."

Multi-modal Interaction: Screen reader & Magnifier. Some participants (P2, P3, P6, P9) used a screen reader in addition to a magnifier to interact with the visualizations. Since simultaneously manipulating both technologies is challenging, the participants seem to rely on one over the other based on the expected benefit. For example, P3 only used the magnifier when he read the title, which is larger in font and shorter in text, but used the screen reader to read the paragraph describing the visualization, which was smaller in font and longer: "I'm looking at the title says daily new hospital admissions by age. (And moved on to the description below) I have my screen reader function, so I'm just going to go ahead and use it." Sometimes there were more data points and labels to examine, such as in the scatterplot that P2 examined (Fig. 5) and he found the screen reader more useful, compared to when he examined a pie chart with seven data points: "the screen reader was a little bit more helpful with the scatterplot."

P2 shared that he wished the screen reader and magnifier could work together more seamlessly. P2 stated, "I think it's always been a problem with the magnification and screen reader compete" when he explained that the focus of the magnifier gets hijacked by screen readers when it's activated. He suggested an interaction to accommodate the advantages of the two technologies. As P2 stated, "Something that would allow a screen reader and magnification to work together more efficiently like a system whereby I can move the magnification around, and the screen reader would tell me what is focused."

4.5.6 Challenges Posed by Visualization Design.

Thin, Light, and Sparse Gridlines & Tick Marks. All participants made comments about gridlines and tick marks, mainly about their thickness and lightness in color and their sparsity. Thin gridlines sometimes went unnoticed, as in the case of P7, who mentioned, "It's just very thin. So if you had that as maybe a quarter inch thick, [I would notice]." The lightness in color, mostly in light gray, made it hard for participants to utilize ticks in visualization reading. P3 wished that the line "could be bolder," and P10 also shared that "if it were bold like the numbers on the far right or the title above, it would be easier to read." A similar sentiment around the tick marks was shared by P4 "If the tick marks were larger, it would help me clarify how graphs are presented."

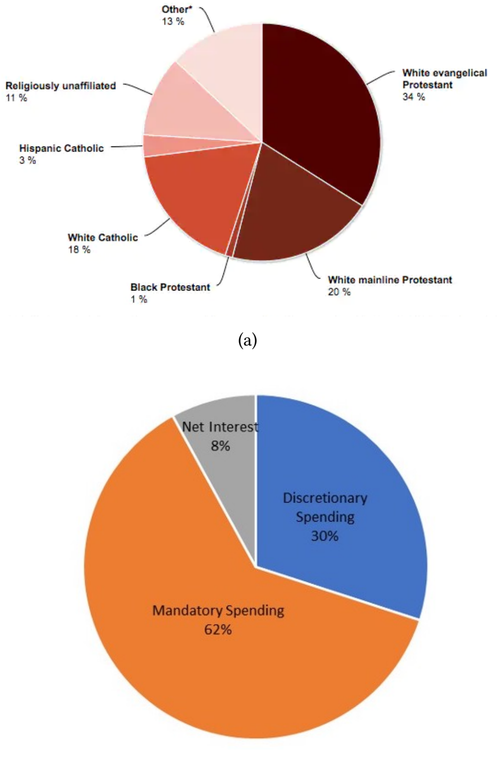
The gap between the tick marks, often aligned with the gridline placements, posed an issue. Since participants looked at zoomed-in views, none or very few gridlines appeared in their views (Fig 6(b)). For example, P3 shared, "The more detailed, the better. Like maybe it shows where 15 (when the tick says 10 and 20)." P10 stated multiple times when examining the visualization, "The gridlines are so far apart," and P1 echoed the sentiment: "I am lack of gridlines."

Participants expressed a desire for more gridlines due to the difficulty they experienced in visually tracing data points to read values. P7 emphasized that "those internal horizontal, vertical grids on a chart, which is very important for a visually impaired person because otherwise, it's really hard to follow." To compensate for the lack of gridlines, some participants, including P7, resorted to moving their mouse cursor horizontally from a data point to the y-axis to maintain tracking. P7 described this process, saying, "Because I can't see them (gridlines) I just do taking my cursor and just doing somewhat of an imaginary line over [here]."

Since tracing back to the y-axis can be costly, we observed that some participants used the nearby labels to infer the value of a specific data point when they could. For example, P5 dragged the mouse cursor to the nearest label (Fig. 11(b)) instead of tracing all the way to the y-axis: "This was easy because it had the numbers [nearby], and you just needed to be able to look at the numbers."

Color, Locations of Marks & Low Contrast between Marks and Background. While participants described their challenges as a "color problem," the underlying cause was often the low contrast that the colored elements create with the background.

While exploring the visualization where the gray color was used to represent the other party (Fig. 5), P3 did not seem to recognize any gray dots. When we asked whether he could find data points for the other party, P3 said "Oh I can barely see them." P7 also did not recognize the circle that encoded lower values, but she recognized something was wrong when she read the label in the middle of those circles (Fig 6(a)). At the end of the session, P7 explicitly mentioned that "gray is very hard for visual impairments." Participants who examined the line chart with a gray dashed line, which represented the average of all ages (Fig 8(a)) found it hard to recognize the line. For example, P4 shared "Some said dash lines are good. Dash line when it's thin, it makes it worse."



(a)

(b)

Figure 10: (a) A pie chart composed with gradual lightness, (b) A pie chart that contains text labels on top of the slices.

Several participants had difficulty distinguishing sections in a pie chart that used similar colors (Fig 10(a)). For example, while P2 was looking for the proportion of a certain religion, he realized that the big chuck that he thought was one slice was actually multiple slices: "Okay, so I see that there are sections that I was missing seeing visually before. I did not see how this bright area was divided. It's because the contrast is not very strong. "

Clustered marks can also be challenging to read. For instance, while P1 was scrutinizing an area with numerous overlapping lines (Fig. 8(a)), he noted the abundance of unused space on the chart and suggested redistributing the data points to prevent the lines from clustering too closely, "There's a lot of empty space on this chart, so move the numbers so the lines can be better separated. Without zooming in, it's nearly impossible to discern anything as they are all tightly bunched together."

It seems that perceived contrast interacts with other attributes of the objects. For example, we observed the interaction between the objects' proximity and perceived contrast. When P5 examined the visualization with yellow and green lines (Fig 11(a)), she had no problem reading the visualizations most of the time. When she examined the area where those two lines were so close together (near 2020 II), she stated that "really hard for me to read," and "I can't see the yellow." We also observed the interaction between the objects' size and the perceived contrast—small size reduces the participants' ability to distinguish colors. P8's color blindness prevented her from seeing red and blue on the bar chart (Fig 7(b)). She could tell the differences between blue and red by their darkness when she looked at the bars. However, she couldn't tell the difference when she looked at the legend: "For some reason, two little dots there are too small to see the difference."

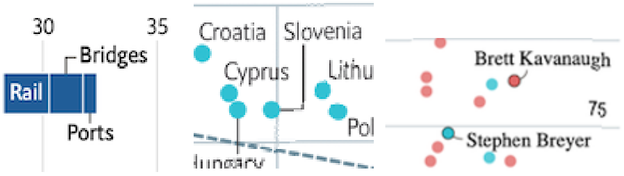
(a) (b)

Figure 11: (a) The original visualization, (b) zoomed-in view. Some participants used the nearby labels to infer the values of the data points.

Organizations. Some schema to organize data points, such as sorting, supports visualization readings by providing some structures to the navigation. P5 mentioned the benefit of sorted charts to streamline her navigation: "I knew, don't look at the top, because they were going to be the highest score. Closer to the bottom, so I went closer to the bottom [to see what category has the minimum value]. " P6 also examined the pie charts sorted by their proportion. When he examined the next chart, which was not sorted, he shared that "increasing proportion decrease in the proportion that could also help."

While certain predictable structures can aid participants in reducing navigation costs, unexpected chart organizations can lead to confusion. For instance, when the y-axis was positioned on the right-hand side instead of the traditional left-hand side, several participants struggled to locate it. P7, while navigating the left side of the visualization in search of the y-axis, queried, "What's the other axis?" Upon moving the mouse and discovering the y-axis on the right-hand side, she questioned, "Is this an axis of something?"

Other Elements on Visualization. Other elements, beyond basic chart elements, were easily missed by many participants because they were often small in size as well as unexpected (Fig. 12). Since some participants' visual conditions did not allow them to fully utilize peripheral vision, the participants could only notice objects when they were focused on them. For example, when P3 examined the scatterplot (Fig 12(b)), he missed the lines to connect the labels and the data points and misunderstood that the labels were associated with the closest marks. After completing all the tasks, the researcher revealed the presence of these lines, he commented that "I have to concentrate on what I'm looking for, and if I'm not, if I don't know it's there, I'm not looking for it, and I might miss it."



(a) (b) (c)

Figure 12: Thin connecting lines between marks and labels to indicate the associations were not discoverable for some participants.

In many cases, units of data points were located far away from the visualizations, such as in the upper right corner. Oftentimes, when participants examined axes in a zoomed view, the unit of data points was not in the view, requiring them to shift their focus back and forth between the axes and the unit. P9 shared "Obviously, they are daily admissions per 100,000 units but sometimes, it is better be the right next to the label because it helps me see." P2 also encountered difficulties, spending considerable time figuring out the unit: "Is this the year or number of days? I didn't see that (unit). Maybe they were there, but I didn't see it. "

While most texts were easily accessible due to their black-on-white or white-on-black contrast, some labels superimposed on colored marks proved challenging to read. For instance, P10 had difficulty discerning the labels on the colored pie chart slices (Fig 10(b)). To improve visibility, P10 suggested relocating the labels outside the pie chart, stating, "I recommend that labels be moved outside of the pie chart [to make them] show up better."

Some Chart Types are Inherently Easier to Navigate. Participants shared that some chart types are more accessible and easily navigable because of their visuals. For example, P7 mentioned, "The bar charts are thicker versus like scatterplot. Anything that's going to be heavier in ink is going to be easier for the visually impaired. So, the bar chart and the pie chart are going to be probably the two easiest charts for a visually impaired person to read. P1 also shared that the pie chart was easier to navigate compared to the line chart: "I like pie charts. Everything is in one place."

4.5.7 Challenges by Analytical Task. After the free exploration of each visualization, participants were asked to answer analytical questions we prepared based on Amar et al. [15]. Participants shared that some tasks were harder to accomplish, whereas some were easier due to the interaction required to complete them. While it took a linear time with respect to the number of data items participants should examine, finding clusters seems to be one of the easiest tasks for participants. Because the task did not involve seeing any details or distinguishing objects, for example, P7 shared, "I looked for the densest area on the chart and so just visually I didn't even really need to look at the X or Y axis, I could just look at the most densely populated area on the chart."

Finding extreme values (e.g., "Which sector has the highest level of contact?") was perceived to be a straightforward task, especially when participants remembered the rough location of the target. However, P4 expressed frustration with having to rely on memory for this task. He mentioned, “If I didn’t know by memorization, then I was between 2021 and 2022 here there’s no information available currently in my view that tells me that, so I just have to like remember it.” When data was sorted, participants carried out the task easily. For example, P8 shared, “This is pretty easy that they’re in line order. They’re lined up.” However, when finding extreme values involved any comparison between two points, participants took more time to compare the two or more data points. For example, P1 tried to identify which of the two peaks is higher to figure out the maximum data point. “So for this one, I just completed a zoomed-out to look at the top. I noticed that they’re both approximately the same, so I just tried tracking my mouse to compare.”

The task of retrieving the value of a specific data point (e.g., “What is the percentage value for *Texas*”?), typically involved two steps. Initially, participants would locate the relevant data point, such as a bar representing Texas. This process often required a time investment proportional to the number of data points. Once the target data point was identified, participants would either find the text label adjacent to the data point or trace it back to the axis to read the value. However, tracing back to the axis could be time-consuming, particularly when the data point was situated on the axis’s opposite side. To mitigate this, some participants expressed a desire for duplicated axes on both the left and right sides, enhancing accessibility regardless of the data point’s location. For instance, P8 suggested, "If this scale this zero, -10, -20, -30 was repeated on the other side, [it would be helpful]."

When participants retrieved data value from pie charts, of which the labels were often located near the slices, we asked participants whether they read out the value from encoded marks (e.g., angle, area) or label. All participants responded that they looked at the labeled number right next to the slice. As P1 shared, “I was just looking at the number.”

To support reading values, several participants suggested a tooltip feature that MS Excel charts offer. For instance, P1 shared, “On Excel, there’s a feature where, if you can scroll over the line itself, it shows you a line that is what line that represents and the value.” P5 also echoed the usefulness of the tooltip feature, but she raised a potential problem when two marks were very close to each other: “Another problem that would come up is, if I put my cursor here, and I have it on the other line, I wouldn’t know if it was foreign or US-born [line].”

Participants generally found tasks involving the determination of a range (e.g., “What is the approximate range of the oil price?”) to be less challenging than tasks requiring the retrieval of specific values. This is likely because the former tasks did not necessitate locating a specific data point. Instead, participants could simply examine the marks located at the extreme ends (either left and right or lowest and highest) to answer the question. As P11 succinctly put it, "That’s pretty straightforward. You look at the highest and the lowest."

Tasks that required the computation of derived values, such as averages or correlations, proved challenging for participants as they required seeing multiple marks at the same time to do mental calculations. This difficulty was similar to the one encountered when constructing an overview, as discussed in Section 4.5.4. The challenge was amplified when participants had to compare two specific points for precision. For instance, P8, when tasked with finding the differences in values between two states in a bar chart, had to first locate the states, retrieve their respective values, and then perform subtraction. She described the challenge as follows: “The hard part was finding the States and then tracking those horizontally to find the percent that they have decreased in a year.” When asked if she could determine the value by comparing the length of the bar difference, she noted the difficulty of alignment due to her limited visual range. Similarly, P3 struggled with the same issue and suggested a feature to capture a screenshot of one view for comparison with another. P3 stated, "If I could take a screenshot, then I could compare both images without the rest of the graph interfering."

5 DISCUSSION

5.1 Summarizing of Findings & Contextualizing Findings with Prior Work and WCAG [3]

The assistive technologies employed by our participants introduced variations in the visualizations viewed by each individual. These variations were primarily due to differences in zoom levels and color filters, resulting in visualizations of varying sizes and colors. Given the diverse vision conditions of our participants, the final view that each participant perceived was even more different. At times, these assistive technologies posed challenges to understanding visualizations due to their inconsistencies or malfunctions. These challenges echoed findings from previous research investigating how individuals with low vision perform daily tasks, such as locating an email or sending a text message [62].

We observed that participants did not leverage, or were not able to leverage, the perceptual benefits visualizations offer. For example, participants did not read out the value of a slice from the angle in a pie chart or compare two bars to understand the difference between two data points. Since participants mostly relied on axes and labels to understand the underlying data, we are unable to discuss how perceptual effectiveness between different encodings impacts participants’ performance. However, certain types of data visualizations, such as bar charts and pie charts, were generally considered more straightforward to navigate than others (e.g., scatterplot), owing to their inherent visual characteristics. Composition with thick marks in the predictable order helped participants to better distinguish marks and navigate efficiently.

The stimuli we sampled from the wild did not strictly follow the available guidelines, particularly in terms of color. This ‘color’ issue in the visualizations caused participants to seek additional references, such as labels. These findings are consistent with a recent large-scale study that meticulously simulated color vision deficiency [16]. Not only the visualization from the wild but the visualization assisted by an inverted filter can still be inaccessible. We observed that one of the visualizations inverted by a participant’s inverted filter was not compliant with WCAG (Fig. 8(b) and 8(c)), demonstrating the challenging nature of resolving inaccessible issues when multiple visual conditions (e.g., light sensitivity vs. contrast sensitivity) interact.

Since most data analytical tasks were done by reading labels from axes and labels, gridlines were one of the important visual aids participants had. According to WCAG, non-text contrast between elements should be at least 3:1 to be distinguishable [3]. We found that most gridlines in the visualization stimuli we sampled from the wild do not have enough contrast with the white background. Accordingly, all participants shared their frustration. One of the design practices for "helpful" gridlines (for sighted individuals) has been contrastive enough to be visible but subtle enough not to obscure the visualization, which is about 0.2 alpha value with a solid black color [60]. When we simulate this, the contrast ratio is 1.6:1, which is lower than the 3:1 that WCAG prescribes for low-vision viewers [3]. Many visualization creation tools [12, 59] support gridlines either by default or with a quick configuration. However, these options were often lower than the desirable contrastive ratio. For example, the default gridlines that ggplot2 provides have a 1.3:1 ratio. In addition to their lightness, participants also wished to have more frequent ticks and gridlines as it aids in tracking data points to axes. The thin black line being used in visualizations to connect between marks and labels was not discoverable for several participants, even though the design meets the guidelines (contrast ratio: 9:5, 3 Pixel) since they were unexpected and therefore did not gain the participants' focus.

We observed that conditions are interrelated as participants who shared seemingly similar conditions experienced the same stimuli differently. We also found that the element's attributes impact perception in a non-linear way. For example, we observed that when the size of the element is small, the discriminability of two lightnesses becomes low. If two elements were closed, perceived contrast decreased. WCAG also mentioned the interaction between the size of the text and the contrast [3]. For example, an LVI may not be able to read small text with a contrast ratio of 5:1, but the person may be able to read a larger text with the same ratio.

WCAG emphasizes proximity between information when conveying relatedness [3]. While most of the time, participants were able to use nearby elements, we observed some cases where proximity was not enough to provide the semantics. For one of the stimuli, two participants did not recognize the nearby element as a legend, even though it was located very close to the visualization. It may be because participants were only able to see the partial view of the legend, not signaling the element and the visualization is related information or due to their unique vision conditions.

Traditional color mapping schemas, such as diverging, sequential, and qualitative color scales, may pose accessibility challenges for individuals with low vision. Our study revealed numerous instances where participants struggled to identify data points, values, and mappings due to the contrast ratio between colored elements and the background. For instance, light green marks were difficult to discern when the visualization employed a green hue sequential scale. Similarly, gray marks representing neutrality were often overlooked. While the Web Content Accessibility Guidelines (WCAG) suggest providing additional visual cues when color is used to signify information[14], none of the stimuli incorporated these cues. This issue is further elaborated in a related blog post[7].

Important context that helps viewers understand visualization is often lost in viewers' zoomed-in view. Specifically, they had no access to 1) legend, 2) axis, 3) unit, and 4) other data points beyond the view. Chartability [30], a well-organized heuristic for testing visualization accessibility, also echoed the importance of the clear labeling practices of this information. To obtain more context, participants traverse around the visualization by employing some strategies to minimize costs. The strategies include relying on memory or prior knowledge to strategize their movements or using nearby labels to contextualize data points in the view. To compensate for their vision conditions, sometimes, participants had to rely on their prior knowledge to infer information. Many participants moved the mouse cursor for tracing, preventing them from derailing, which can happen if they depend solely on vision.

5.2 Importance of Bottom-up Approach to Design Visualizations for Accessibility

The design process often takes a top-down approach that starts by identifying relevant design principles and applying them to the design. An example is applying the perceptually effective channels using the data model, such as applying the position encodings when two quantitative variables need to be visualized. However, as our study has shown, the accessibility of a visualization can be impacted during the rendering process. For instance, when two data points are placed too closely, with barely 1 pixel of white space between them, this can pose significant challenges for LVIs, hindering them from distinguishing between the two marks [9]. What if designers do not blindly apply the design principles but also adapt or re-adjust the design based on the rendered outcome? For instance, if similar lightness colors are assigned to adjacent marks, color palettes can be reassigned to the categories to enhance contrast. If lines appear too close, adjusting the aspect ratio can create more space between the lines. In cases where marks become too congested, consideration of alternative scaling methods, not sticking to zero-based scales. Refining the design based on the rendered results using accessibility checklists such as chartability [30] and, furthermore, reflecting on these cases back to the design principles will ensure accessibility in both the short term and the long term.

5.3 Design Goals for a Personalized Tool for LVIs

While universal guidelines strive to accommodate a wide range of visual conditions and situational factors, they may not always sufficiently cater to everyone's unique needs. Furthermore, the existence of poorly designed visualizations is inevitable, as adherence to these guidelines is not always guaranteed. Based on our observations, we propose the development of a personalized tool, such as a browser plug-in. This tool would re-render visualizations to suit each user's specific needs, thereby facilitating the comprehension of visualizations and the completion of analytical tasks. We outline the objectives for designing such a tool and discuss potential implementation strategies for each feature to support these goals.

Goal 1: Learn and accommodate the visual condition of the viewer. As a first step, the tool should understand the viewer's visual condition to accommodate and parameterize them to systematically re-render the visualizations. Our study findings implied that the viewer may not be able to articulate their conditions accurately when verbally prompted. Also, their surroundings, including light conditions and the monitor's setup (e.g., brightness, distance, size), can change the visual perception [65]. We envision the tool can elicit their conditions *graphically* on the fly to understand their *situational vision conditions* with their surroundings. For instance, a digital grid with varying letter sizes could assess visual acuity and field loss by asking viewers to identify visible letters. Additionally, an interface testing for contrast sensitivity and color blindness could help gauge the viewer's ability to distinguish colored objects.

Goal 2: Support constructing overview. The tool should facilitate the construction of an overview, which is crucial for various analytical tasks. Based on the study findings, we envision this overview as a resized visualization that fits within the viewer's zoom level. The tool should be capable of reconstructing the visualization to effectively communicate the layout of the visualization components (e.g., axes, units) and annotations, as well as the overall data trend. To visualize the data trend, the details should be abstracted to ensure visibility. Clustering data by leveraging the notion of hierarchy that prior work applies for screen reader users [69] or sampling data points would be a good option.

Goal 3: Providing Contexts to Minimize Navigation. In a zoomed-in view, the tool should provide extensive context to minimize navigation effort. For instance, it could automatically show virtual axes with marks, as most tasks involve reading axis values. It should also display units and other essential information, like the visualization's description, easily accessible via a hotkey without needing cursor movement.

To aid in locating specific data points, the tool should enhance search functionality, allowing viewers to either see a data point's location or automatically center the view on it upon request. Additionally, for comparison tasks, features like freezing one view while focusing on another can significantly reduce the need for back-and-forth navigation between data points.

Goal 4: Re-render to enforce guidelines. Since visualizations in the wild have high chances of being inaccessible, the tool should detect the various visualization components, including ticks, gridlines, marks, and texts, to enforce the guidelines. If the color is being used as an encoding, the tool can adjust the color based on the viewer's condition or use other visual cues to convey the mapping information.

Goal 5: Leveraging visual perception. Using a screen magnifier, LVI viewers may struggle to fully leverage their visual perception for tasks like estimating magnitudes or comparing marks in visualizations. Since the tool can learn about the viewer's specific visual conditions, including their viewing fields and areas of spot loss, the tool can dynamically re-render visualizations to make the most of the viewer's remaining visual capabilities. For instance, it could render important data points or patterns within the viewer's effective viewing field.

5.4 Limitations & Future Work

We prepared 12 visualizations with four different types, including bar, pie, line charts, and scatter plots, known to be most widely used in the wild [25]. While we carefully varied the design of the visualizations in choosing stimuli to observe broader aspects of LVI's experience, LVIs may interact differently with more complex types of visualizations, such as sunburst charts or network diagrams. Future work could explore LVI's interactions with these advanced visualizations, where familiarity with structure is typically lower.

While an online study may be the best solution for reaching a broader population [17, 52], different insights could be derived with in-person studies. Prior work shows that LVIs make physical adjustments (e.g., changing postures, getting closer to the monitor) in addition to using digital assistive technologies to better understand browsing contents [62]. In-person studies could more fully capture these physical strategies in visualization reading scenarios, and eye-tracking could add insights into their viewing behaviors.

In the analysis, it was challenging to reason how participants' behaviors were influenced by their visual functions. In other words, there were no means to observe how each visual function, for example, light sensitivity, contributes to the challenges participants face, partly due to interrelated symptoms and varying severity among individuals. Future studies could control each function individually through simulation or recruit participants with similar functions, differing in just one, to better understand each function's impact on visualization reading. In the future, we envision a controlled study where we can control each function at a time (through simulation) or recruit participants who share mostly similar functions but differ in one function to further understand the impact of each visual function in reading visualizations.

Lastly, as outlined in Section 5.3, developing a personalized tool tailored to an individual's condition and needs would be a significant next step. While we have motivated the use of a tool that alters visualizations post-creation to make them accessible, we do not endorse an approach where accessibility is treated as an ad-hoc consideration. Visualization authors should always adhere to established guidelines when creating visualizations. The community should strive to advocate for design practices that are inclusive of everyone with varying abilities. Meanwhile, some automated approaches may help mitigate issues of inaccessibility.

6 CONCLUSION

In recent years, visualization accessibility has gained momentum, driven by a commitment to providing equitable access to data for individuals with visual impairments. We bridged the knowledge gap by supporting an oversight population, namely low-vision individuals, who rely on their remaining vision to interact with the world. Our work highlights the importance of inclusive design in making visualizations accessible to a broader audience, considering the unique needs and challenges faced by individuals with low vision.

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