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LONG PAPER

Enhancing statistical chart accessibility for people with low vision: insights from a user test

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Abstract

A remote user test was performed with two versions (one accessible and one non-accessible) of three types of web-based charts (horizontal bar chart, vertical stacked bar chart, and line chart). The objectives of the test were: (a) to validate a set of heuristic indicators for the evaluation of the accessibility of statistical charts presented in a previous work (Fariñas Falcón et al. in Mediocentro Electrónica 21(1):65–68, 2017); (b) to identify new barriers and preferences for users with low vision in the access and use of this content not previously contemplated. 12 users were tested, with a variety of conditions associated with low vision: low visual acuity (6 users), reduced central vision (2 users), reduced peripheral vision (2 users), blurry vision (1 user), sensitivity to light (3 users), Nystagmus (2 users) and color vision deficiency (CVD) (4 users). From a quantitative standpoint, accessible versions of charts were more efficient, effective, and satisfactory. From a qualitative point of view, results verify the relevance of heuristics H2, Legend; H3, Axes; H6, Data source (as data table); H10, Safe colors; H11, Contrast; H12, Legibility; H13, Image quality; H14, Resize; H16, Focus visible; H17, Independent navigation; related to the proposed tasks. As new observations, tooltips were highly valued by all users, but their implementation must be improved to avoid covering up significant parts of the charts when displayed. The data table has also been frequently used by all users, especially in the non-accessible versions, allowing them to carry out tasks more efficiently. The position and size of the legend can be a significant barrier if it is too small or appears in an unusual position. Finally, despite the limitations related to color perception, some users prefer color graphics to black and white, so, to target all profiles, it is necessary to redundantly encode categories with colors and patterns as well.

Keywords Low vision · Statistical charts · Data visualization · Web accessibility · User test · Heuristic evaluation

1 Introduction

The number of people with low vision worldwide is significant. Globally, in 2020, an estimated 43,3 million people were blind. On the other hand, it is estimated that 295 million people have moderate and severe vision impairment; 258 million have mild vision impairment; and 510 million have visual impairment from uncorrected presbyopia. Globally, between 1990 and 2020, the number of people who were blind increased by 50.6% and the number with moderate and severe vision impairment increased by 91.7% [1]. The same study predicts that by 2050, 61 million people will be blind, 474 million will have moderate and severe vision impairment, 360 million will have mild vision impairment, and 866 million will have uncorrected presbyopia.

Each disability affects visually impaired people differently, resulting in a significant variety of user profiles [2]. However, in all cases, low vision is a visual condition

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characterized by a substantial reduction in sight that cannot be corrected with lenses, medication, or surgery. Low vision profoundly impacts the daily lives of those who experience it [2] due to the prevalence of visual information in the acquisition of knowledge and daily activities. Visual information is often more detailed and richer compared to auditory or tactile information. As a result, much of our technology has been designed with a focus on sight.

In this context, the total or partial loss of visual perception can lead to a dramatic reduction in autonomy, given its crucial role in fundamental daily tasks such as learning, mobility, access to information, and social inclusion and participation.

Low vision is defined by assessing a person's visual acuity and field of vision. Visual acuity measures the ability of the visual system to distinguish between two closely spaced points at a specific angle [3]. Field of vision, or peripheral vision, refers to the total visual area in degrees while the central point of focus remains fixed [4]. Generally, an individual is considered to have low vision if, even with the best optical correction, her visual acuity falls below 20/60 [4] or 20/70 [5], or their field of vision is less than 20°.

Low vision encompasses individuals with visual impairments other than blindness which cannot be fully corrected with lenses. This category includes various user profiles resulting from congenital origins or different eye conditions and diseases such as cataracts, glaucoma, macular degeneration, or diabetic retinopathy. Each person may exhibit varying degrees of visual acuity and field of vision, along with specific challenges related to contrast sensitivity, light or glare sensitivity, and color perception.

For example, macular degeneration is an eye disease that can result in blurred or absent vision in the central field, in areas known as scotomas. As a consequence, individuals with this condition often rely on their peripheral vision [2]. Glaucoma leads to the loss of peripheral vision, accompanied by a blurred central area, making tasks like reading, and seeing detail exceptionally challenging [6]. Cataracts can cause vision to become blurred or hazy, especially in bright light [2], and may also affect color perception [7]. Ocular albinism is characterized by reduced visual acuity and heightened sensitivity to brightness and light [8]. Nystagmus is associated with involuntary, uncontrollable eye movements linked to neurological issues [9]. Retinoschisis impacts both central vision acuity and peripheral vision, which can be lost if the inner layer of nerve cells detaches from the outer layer [10]. Multifocal chorioretinitis leads to vision loss, blurry vision and other symptoms [11]. Stargardt's disease may manifest as gray, black, or hazy spots in the central vision, light sensitivity, slower adaptation to changes between light and dark environments and, in some cases, color blindness [12]. Finally, color vision deficiency (CVD), also known as color blindness, can be acquired but usually is a genetic condition [13] that affect the expression of the full complement of normal cone photoreceptors. CVD presents a wide range of severity: anomalous trichromacy, dichromacy, and monochromacy (complete inability to perceive any colors) [14].

Another challenge associated with low vision is that many of the vision problems mentioned tend to manifest as individuals age, either suddenly or gradually. These visual impairments often occur later in life, making it more challenging to acquire new skills and adapt to assistive technologies that may be unfamiliar.

Furthermore, people with low vision utilize a wide range of assistive technologies, with screen magnifiers being a prominent choice, followed by screen readers, zoom features integrated into web browsers, and high-contrast settings. This diversity in profiles, barriers, and assistive technologies presents a significant challenge in meeting the specific needs of each group through a single, universally effective design.

This research employs a user-centered approach to gain a deeper understanding of the obstacles faced by individuals with low vision when accessing data visualizations. In contemporary society, data permeates nearly every aspect of our lives [15], encompassing information dissemination, education, research, and leisure activities. As Kim et al. aptly stated, 'our society is becoming data-driven' [16]. Consequently, the ability to comprehend and manipulate data is crucial for individuals to grasp the world, make informed choices, access scientific findings, grasp abstract scientific concepts [17], and retrieve public health and social care information [18].

In our data-driven era, one of the primary challenges is to elevate data literacy. Data literacy encompasses the ability to proficiently comprehend, analyze, and communicate data [19]. In today's society, data literacy is an indispensable skill [16, 20, 21]. It involves not only the capacity to read and interpret charts and data tables but also the ability to critically assess data quality, recognize biases, and grasp the implications of findings [22].

Data visualization, particularly statistical charts and various graphical representations, facilitates the efficient processing of information. Schepers [23] regards data visualization as an inherent assistive technology, a form of cognitive accessibility that leverages our visual system to ease the interpretation of tabular data [24]. Charts enable the visualization of abstract concepts and intricate relationships, which may be challenging to comprehend through alternative data formats [25], and facilitate the identification of patterns and trends in data [26].

In the realm of scientific communication, charts serve as concise and accessible means to convey the primary outcomes of extensive research endeavors [27–29]. Consequently, data visualization is recognized by several authors as an essential skill, not only for the general populace [16, 20] but also for future researchers [21].

In this context, obstacles to accessing data can exacerbate societal inequalities, particularly among individuals with disabilities, who already contend with various social and economic disparities. Recent examples have highlighted challenges in accessing public health information [30–32], political data [33], preserving professional autonomy [34], and securing quality education [35, 36].

Conversely, accessibility issues that have traditionally affected data visualizations, including statistical charts, also pose challenges for search engines. These engines struggle to crawl, index, utilize, and display these representations on their results pages, primarily due to them being static bitmap images or, at best, vector images with limited accessibility features despite the potential of this format [37].

In large part, this issue arises from content authors (such as designers, journalists, data scientists and researchers) lacking awareness of the accessibility barriers individuals encounter when trying to access their data visualizations. Furthermore, they may be unaware of the available techniques and solutions to address these barriers [38].

The primary objective of this article is to elucidate the needs and perspectives of individuals with low vision, with the aim of identifying key issues related to inaccessible charts. Ultimately, the authors seek to propose specific solutions that can enhance the accessibility of data visualizations.

2 Related research

While the field of data visualization has experienced exponential growth in recent years, research on the accessibility of visual artifacts within this discipline has not kept pace [39]. Presently, there is a rising interest in enhancing the accessibility of data visualizations for individuals with intellectual disabilities and the cognitive barriers caused by conventional design guidelines related to the chart type selection, chart embellishment conventions, and the representation of data through continuous marks versus discrete marks [40]. However, most of the related research on accessible data visualization and charts has predominantly focused on barriers to visual access [16, 39, 41], research methodologies applicable to accessibility [41, 42], practitioner-implemented solutions [43], and the analysis of the impact of elements such as image captions or alternative text [44–47].

Additionally, considerable attention has been given to the development of specific solutions and techniques aimed at facilitating data access. These include, for instance, the use of 3D printed maps and icons [48], tactile representations such as organic node-link diagrams, grid node-link diagrams, adjacency matrices or Braille lists [49], audio-tactile charts in SVG format optimized for embossers [50]; and the incorporation of natural language descriptions to provide context and insights [51]. Additionally, data sonification techniques [52] employ varying tones in terms of pitch and loudness to guide users through charts, often using a combination of MIDI sounds, synthesized speech, and pre-recorded audio files [53].

Other approaches involve chart image detection and classification to identify the chart-types, generate screen reader-compatible summary descriptions, export data to other formats like data tables, and create new, more accessible data visualizations based on existing ones [54]. Specific image processing algorithms are utilized to extract pertinent information from raster images and generate automated textual descriptions [55, 56], while deep neural network methods are employed to extract data from charts, including chart types, labels and relevant data, and convert them into vector charts format [38].

Some proposals enable users to navigate and interact with line charts using natural language commands and a Text-To-Speech (TTS) engine, facilitating specific queries about the chart's content [57, 58]. Hybrid systems are designed to convey information through different senses, such as sight, touch, sound, or muscular resistance (haptic interfaces) [59]. There are even structured musical stimuli used to convey simple diagrams [60].

These techniques can be categorized into chart classification, text recognition, data extraction or data summarization [61], all of which aim to create alternative representations or provide users with access to chart information through their assistive technology.

Despite the higher prevalence of individuals with low vision, existing scientific literature has predominantly centered on blind individuals [62, 63], further marginalizing a group that remains relatively unknown to society [64]. Low vision users exhibit notable distinctions from blind individuals, and many within this group use their residual vision in their daily life as much as possible [65, 66], even if it implies continual adjustments to various interface aspects [65] or the adoption of uncomfortable or strained positions in front of screen.

User studies addressing the accessibility of data visualizations and statistical charts have primarily concentrated on blind individuals [38, 41, 49, 52, 57, 60, 67–70], with only a few including individuals with low vision [48, 71, 72] or color vision deficiency (CVD) [73, 74]. The dearth of studies aimed at identifying the needs and preferences of users with low vision underscores the need for further research in this domain. Notably, research specifically focusing on statistical charts -a content type integral to various key sectors such as education, research, communication, and business, among others- remains largely scarce. To address this gap,

Table 1 Alcaraz et al.'s [75] list of heuristics with their description

ID	Short name	Heuristic
H1	Title	Does the chart have a brief and descriptive title that helps users identify it among others appearing on the same page, as well as navigate between them?
H2	Legend	If the chart uses shapes, color or patterns encodings is there a legend to decodify them?
H3	Axes titles	If the chart needs axes, are they visible and have appropriate, concise and clear labels and titles?
H4	Caption	Does the chart have a caption to help understand it?
H5	Abbreviations	Are all the abbreviations in the chart expanded?
H6	Data source	Does the chart include information about its source (institution, date and URL of dataset)?
H7	Print version	Is there an optimized version for printing available?
H8	Short text alternative	Does the chart provide a text alternative that briefly informs about its contents and helps users decide if they want more information?
H9	Long description	In case the text alternative does not adequately convey the information provided by the chart, does the chart provide a textual long description
H10	Safe colors	If the chart uses colors to provide information, is the color scheme safe for the different types of color vision deficiencies, including achromatopsia (total absence of color vision)?
H11	Contrast	Does the visual presentation of text and background have a contrast ratio of at least 4.5:1, and the non-text elements of the chart a contrast ratio of at least 3:1?
H12	Legibility	Is the text included in the chart legible (sans-serif font, font size of at least 16px or 12pt, line spacing of at least 1.5, no abuse of capital letters, bold or italics)?
H13	Image quality	If the chart is provided as a bitmap image, does the image have sufficient quality for a clear visualization and does it support a zoom of at least 200% without blurring or pixelation?
H14	Resize	Can the chart be zoomed up to 200% without an assistive tool and without loss of content or functionality?
H15	Without disturbing elements	Does the chart have any disturbing element like watermarks that hinder the visibility of the chart?
H16	Visible focus	When an element of the chart (lines, bars, points...) receives the focus, is there a visual indication of it?
H17	Device independent navigation	Is it possible to navigate between the marks and elements of the chart with keyboard, mouse and gestures?
H18	Customization	Is it possible to customize the chart (color scheme, contrast, typography...) with assistive technologies or with a resource-specific customization system?

the authors have developed a set of heuristic principles for assessing the accessibility of such data visualizations [75] (see Table 1).

Heuristic evaluation (HE) stands as one of the most commonly used and effective usability assessment techniques that do not require direct user involvement. HE is a method within the field of usability engineering, employed to identify issues related to usability within a user interface design. It plays a crucial role in identifying and resolving these issues as part of an ongoing design enhancement process. In HE, a small group of evaluators inspects the interface and evaluates its adherence to established usability principles, often referred to as "heuristics", "heuristic indicators" or "heuristic principles" [76].

Compared to an accessibility evaluation conducted using the WCAG as a reference, HE offers several advantages, including greater conciseness, memorability, meaningfulness, and comprehensibility of its principles [77].

On the other hand, domain-specific heuristics typically yield more effective and efficient results compared to general guidelines like WCAG, which primarily focus on website analysis [78].

A notable exception to the lack of research in this field is the set of heuristic indicators put forth by Elavsky and colleagues [79, 80], published subsequent to the development of the authors' own set of heuristics. Elavsky and his co-authors' recommendations are intended to assist visualization designers, journalists, and other practitioners in assessing the accessibility of data-driven visualizations. Their proposal encompasses a total of 50 heuristics, with 14 of them deemed critical, organized into 7 principles (perceivable, operable, understandable, robust, compromising, assistive, and flexible). These principles draw inspiration from the web content accessibility guidelines (WCAG) but have been extended and tailored to address the unique requirements of data visualizations. While aiming to meet the needs of a broad user spectrum, it is noteworthy that 31 of the 50 proposed principles specifically address barriers that may impact users with low vision. Table 2 provides a comparison between the heuristics proposed by Alcaraz et al. and those suggested by Elavsky et al. concerning individuals with low vision.

Table 2 Mapping between the heuristic principles proposed in previous works and those proposed by Elavsky

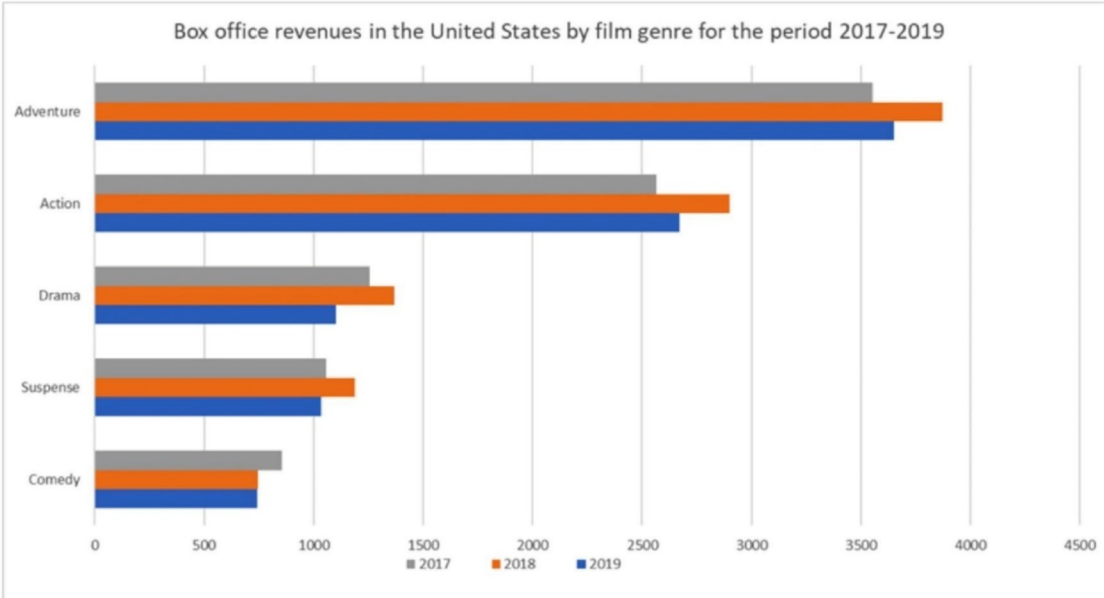
Alcaraz et al.'s set of heuristics	Related chartability heuristics
H1 Title	No title, summary, or caption
H2 Legend	Data in text is not human-readable
H3 Axes titles	Data in text is not human-readable
H4 Caption	No title, summary, or caption Metrics and variables are undefined Statistical uncertainty isn't clearly communicated
H5 Abbreviations	Axis labels are unclear or missing
H6 Data source	No table Table/data is static
H7 Print version	–
H8 Short text alternative	Content is only visual
H9 Long description	Content is only visual Visually apparent features and relationships are not described
H10 Safe colors	Color is used alone to communicate meaning Not CVD-friendly
H11 Contrast	Low contrast Low contrast on interactive elements Keyboard focus indicator missing, obscured, or low contrast
H12 Legibility	Small text size Spacing is inappropriate
H13 Image quality	–
H14 Resize	Zoom and reflow are not supported
H15 Without disturbing elements	Meaningful elements can be distinguished from each other
H16 Visible focus	Keyboard focus indicator missing, obscured, or low contrast
H17 Device independent navigation	Interaction modality only has one input type Controls override AT controls Inappropriate tab stops Complex actions have no alternatives Information cannot be navigated according to narrative or structure
H18 Customization	User style change not respected User's text adjustments are not respected Contrast and textures cannot be adjusted

3 Methodology

The development and validation of the heuristics by Alcaraz et al. followed formal and systematic methodology by Quiñones et al. [81] for creating usability heuristics, comprising eight key steps: (1) exploratory stage (literature review); (2) experimental stage (data analysis to retrieve additional information); (3) descriptive stage (select and prioritize the most important collected information during stage 1 and 2); (4) correlational stage (reconcile the domain features and functionalities with existing heuristic indicators); (5) selection stage (review the list of heuristic principles created); (6) specification stage (formal specification of each heuristic principle); (7) validation stage (experiments to determine the effectiveness and efficiency of the heuristic set); (8) refining stage (refine of the heuristic principles with the conclusions resulting from the previous stage.

Step seven involves the validation of the heuristics set through a series of experiments, assessing their effectiveness and efficiency. This validation process employs the following methods: (a) heuristic evaluation (mandatory): this method is a crucial part of the validation process; (b) expert judgment (optional): experts may be consulted to provide additional feedback, enhancing the validation process; (c) user testing (when necessary): user testing is employed to complement the validation process as needed.

The complete list of heuristics and their definitions is shown in Table 1. These heuristics were validated against WCAG 2.1 [82] in previous research through the analysis of published charts in several contexts: digital media [83], public health information, [31] and scholarly articles [84], with good results. In practical terms, domain-specific heuristics enable the detection of a higher proportion of unique problems, a more even distribution of problems across principles, the identification of a greater number of severe problems, and a more precise identification of specific issues.



Box office revenues in the United States by film genre for the period 2017-2019			
Genres	**2019**	**2018**	**2017**
Comedy	740	746	856
Suspense	1034	1190	1056
Drama	1103	1369	1256
Action	2671	2898	2564
Adventure	3651	3871	3552

Fig. 1 Non-accessible bar chart created with Excel with an additional table in text format

3.1 Materials and methods

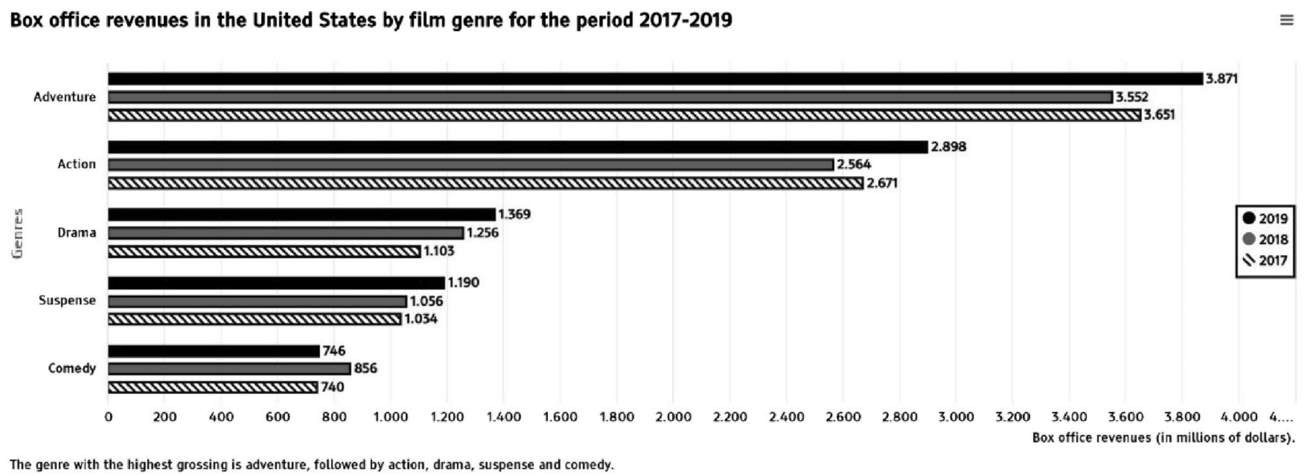
In this study, a second validation of the heuristic set with users is carried out, because users contribute with a new perspective and identify problems that experts cannot always detect [85, 86]. Special attention is paid to new possible barriers [87], and to the characteristics and needs of every specific profile [88]. According to Brajnik [87], "a barrier is any condition that hinders the user's progress towards achievement of a goal, when the user is a disabled person".

For the study, a series of synchronous, moderated, and remote user tests were carried out. The tests consisted of solving tasks for which users had to consult a set of web-based charts that had been created. In total, two different versions of three charts (horizontal bar chart, vertical stacked bar chart, and line chart) were generated: one accessible, created following the abovementioned heuristic guidelines [89], and another non-accessible version. The specific types of charts were chosen based on their popularity and adoption.

Despite the significant diversity among the profiles that participated in the user test, it was decided to utilize a single version for the non-accessible charts. This decision aimed to prevent a substantial increase in the time required to conduct the test and to minimize unnecessary and undesirable fatigue among the users. In the same sense, the color scheme selected for the accessible charts is intentionally kept as "neutral" as possible, utilizing black and white, which is safe for all colorblind profiles. In the case of non-accessible charts, the color scheme and layouts are based on the defaults offered by Microsoft Excel. This choice also enables us to evaluate the accessibility of charts generated automatically by this tool, particularly when they are not customized by their creator.

The non-accessible charts were generated by Microsoft Excel (2019 MSO 16.0.10356.20006 Windows) using the tool's default options to create a chart of each of the selected types and generating an automatic export in HTML format (Fig. 1). Automated export of charts to HTML format using Excel involves converting the original vector image to a low-quality bitmap image. The export included the chart data table in text format.

The accessible versions were created using the Highcharts JavaScript library (v. 8.0.0), including many of its accessibility options with the aid of its accessibility module: screen reader support, long description, keyboard navigation, the use of patterns as an alternative to color, a visual indicator when a mark of the chart receives the focus, and a table with the chart's data, as well as a tooltip functionality that complements the legends, providing information on the value associated with each mark when the focus points to it



Genres	2019	2018	2017
Adventure	3871	3552	3651
Action	2898	2564	2671
Drama	1369	1256	1103
Suspense	1190	1056	1034
Comedy	746	856	740

Fig. 2 Accessible bar chart created with Highcharts

(Fig. 2). All charts, questions and the results of the test are available online.[1]

3.2 Procedure

We designed five identical tasks for both versions, utilizing fictitious data and scenarios in a within-subject design (the same users participated in both conditions). To minimize learning effects, we modified the values represented in each version of the chart.

In defining these tasks, we drew from the categories proposed by Brehmer and Munzner [90], with a focus on tasks related to information consumption, particularly relevant in the context of public information. These tasks encompassed the following aspects: searching for unknown targets in known locations (browse), searching for unknown targets in unknown locations (explore), comparing multiple subsets of targets (compare), and summarizing targets, including the entire set of targets (summarize).

Tables 3, 4 and 5 show tasks, typology of task [90], objectives and related heuristics.

For each task, the moderator read the explanation before starting, asked for questions from the participants, and explained subsequently. We employed the "think-aloud" method as our approach for this study. This method is commonly utilized in user studies to gain insights into the cognitive processes of users as they perform tasks [91]. It has proven to be a valuable and reliable technique due to its minimal disruption of participants' thought processes [92]. In this method, participants are instructed to verbally articulate their thoughts while engaging with tasks, essentially vocalizing their inner dialogues. Moreover, participants are encouraged to explain what barriers or difficulties they encounter. Another advantage of this method is its avoidance of interpretation by the subjects and its simple verbalization process, making it an objective approach [92].

Metrics related to effectiveness (percentage of completion per task), efficiency (time per task), and satisfaction (measure of expectations, with a simplified 5-point Likert scale from 1, not at all complicated, to 5, very complicated) were collected during the test. Qualitative measures focused on detecting the barriers encountered by users and on analyzing the strategies and workarounds used by users to overcome the barriers they faced. After the test, users were asked for their favorite version of each chart, and informal comments were promoted. This approach integrated the "think-aloud" method with a follow-up interview, during which the moderator specifically inquired

[1] https://www.ub.edu/adaptabit/charts-accessibility/user-test/.

Table 3 Bar chart tasks, objectives and related heuristics

Task	Typology of task	Objective	Heuristics related
Which genre and in what year did cinema get the most box office takings?	Search > explore	Compare bar chart lengths by reviewing the entire chart	H2, H3, H10, H11, H12, H13, H14, H16 and H17
Which genre and in what year do the ticket sales approach 3 billion?	Search > explore	Understand grid marks, compare bar chart length versus grid within the entire chart	H2, H3, H10, H11, H12, H13, H14, H16 and H17
In what year does the Drama genre generate most sales?	Search > explore	Search for a specific datum by reviewing a category	H2, H3, H10, H11, H12, H13, H14, H16 and H17
In what year does the Action genre generate most sales?	Search > explore	Search for a specific datum by reviewing a category	H2, H3, H10, H11, H12, H13, H14, H16 and H17
Between the Drama and Suspense genres, which of the two grossed the most ticket sales in 2017?	Query > compare	Find and compare two specific marks by focusing on a part of the chart	H2, H3, H10, H11, H12, H13, H14, H16 and H17

Table 4 Stacked bar chart tasks, objectives and heuristics related

Tasks	Typology of task	Objective	Heuristics related
How many shoes were sold in September 2019?	Search > browse	Search for a specific bar on the timeline and look for the specific category in the stacked bar	H2, H3, H10, H11, H12, H13, H14, H16 and H17
In which month of 2018 were less shoes sold?	Search > browse	Understand year encoding; compare bar lengths of one category by reviewing the entire chart	H2, H3, H10, H11, H12, H13, H14, H16 and H17
Considering the 2-year sale, in what month were the most shoes sold?	Search > explore	Compare total bar lengths by reviewing the entire chart	H2, H3, H10, H11, H12, H13, H14, H16 and H17
Between the 2 years, in what month did sales closer to 1000 shoes occur?	Query > summarize	Understand grid marks, compare bar length to grid in the chart	H2, H3, H10, H11, H12, H13, H14, H16 and H17
In what month is there the biggest difference between 2018 and 2019?	Query > compare	Understand year encoding; compare the two categories in the stacked bar within all bars; do some calculations	H2, H3, H10, H11, H12, H13, H14, H16 and H17

Table 5 Line chart tasks, objectives and heuristics related

Tasks	Typology of task	Objective	Heuristics related
In what month and airport have more flights been flown?	Query > summarize	Locate higher value by reviewing the entire chart	H2, H3, H10, H11, H12, H13, H14, H16 and H17
In what month has El Prat Airport had the highest number of flights?	Query > summarize	Understand category encoding; locate higher value of a specific category by reviewing the entire chart	H2, H3, H10, H11, H12, H13, H14, H16 and H17
In what month has Barajas Airport had the lowest number of flights?	Query > summarize	Understand category encoding; locate lower value of a specific category by reviewing the entire chart	H2, H3, H10, H11, H12, H13, H14, H16 and H17
Which airport had the highest number of flights in October?	Query > compare	Understand categories, compare two specific point values on a section of the chart	H2, H3, H10, H11, H12, H13, H14, H16 and H17
In which month and airport were the number of flights nearest to but not higher than 50.000 flights?	Query > summarize	Understand grid marks, compare points to grid by reviewing the entire chart	H2, H3, H10, H11, H12, H13, H14, H16 and H17

about any potential barriers or issues that users may not have verbalized during the tests.

Table 6 Information of participants in the user test

ID	Gender	Age	Education	Condition	Assistive technology
1	M	18	Middle school	Ocular albinism, nystagmus, and low vision with visual acuity 1/10 with the best correction	Browser's zoom and Windows high contrast mode
2	M	70	Bachelor's degree	Glaucoma with 30% visual impairment in the left eye and visual acuity in the right eye, movement of the hand and left eye 0′35 130° − 1′25–0′45 + 4 R − 0′5	Windows magnifier and high contrast mode in combination with handheld magnifying glass
3	M	30	Bachelor's degree	Ocular albinism with visual acuity of 10%	Windows magnifier
4	M	58	Bachelor's degree	Glaucoma with visual acuity 0–10	Handheld magnifying glass
5	F	26	Bachelor's degree	Brain injury affecting peripheral vision and reduced central vision at long distance with 70% visual field involvement	Browser's zoom
6	M	26	Bachelor's degree	Stargardt's disease and visual acuity of 5% and difficulty in the perception of all colors	Zoom and inverted colors in MacOS
7	M	79	Bachelor's degree	Wet macular degeneration	Windows magnifier and high contrast mode in combination with handheld magnifying glass
8	F	51	Bachelor's degree	Stargardt's disease with visual acuity of 7%, and difficulty in color perception	Windows magnifier
9	F	76	Elementary school	Achromatopsia and high myopia with visual acuity of 15%	Browser's zoom
10	M	23	Bachelor's degree	Juvenile retinoschisis	Windows magnifier and browser's zoom
11	F	28	Bachelor's degree	Multifocal chorioretinitis	Browser's zoom
12	F	49	Bachelor's degree	Bilateral central nystagmus of unknown etiology. Difficulty perceiving certain colors	Windows magnifier and high contrast mode in combination with screen reader

3.3 Participants

To recruit participants, the authors distributed a questionnaire to individuals with low vision who are members of the Asociación Discapacidad Visual de Cataluña: B1 + B2 + B3 (Visual Disability Association of Catalonia, Spain). The questionnaire collected information on several factors, including: (a) age; (b) gender; (c) type and degree of visual impairment; (d) visual field affection and degree of affectation; (e) visual acuity; (f) color blindness; (g) light sensitivity and contrast sensitivity; (h) other disabilities that may impede computer use; and (i) level of education.

A total of 12 users were recruited, and with a snowball strategy from the early contacted users. Initially, tests were planned to be held in B1 + B2 + B3 offices, but due to access restrictions during the COVID pandemic, they were repurposed as remote tests with Zoom platform. Because of COVID and also due to the barriers expected to be encountered in the use of videoconferencing platforms, many of the previously contacted users (more than 20) refused to participate after having initially accepted.

On the other hand, remote tests allowed users to answer the tests from their own homes, with their personal computer equipment and assistive technology, with the ideal setup. Consent forms were sent to participants prior to the session so they could read, print, and sign them.

The sample was composed of 58.33% (7) men and 41.66% (5) women; 83.33% (10) of the users had higher studies and only two users (16.66%) had middle school and elementary school studies, respectively. The age of the participants was between 18 and 79 years, the average being 42,3 years. The sample included a variety of conditions associated with low vision: low visual acuity (6 users), reduced central vision (2 users), reduced peripheral vision (2 users), blurry vision (1 user), sensitivity to light (3 users), Nystagmus (2 users) and color vision deficiency (CVD) (4 users). Table 6 shows a detailed description of each user.

4 Results

Quantitative (user study results) and qualitative results (observations) are detailed as complementary views of the test.

4.1 User study results

As mentioned, effectiveness was measured dividing the number of completed tasks by the number of attempted tasks (percentage of completion per task). Efficiency was measured with time per task.

Table 7 Effectiveness and efficiency by chart type and version

Chart	Average percentage of solved tasks	Average efficiency (time in seconds) for solving all tasks	Median efficiency (time in seconds)
Accessible bar chart	91.67% (55)	21.30	14.0
Non-accessible bar chart	98.33% (59)	44.58	21.0
Accessible stacked bar chart	88.33% (53)	23.20	19.0
Non-accessible stacked bar chart	81.67% (49)	33.38	29.0
Accessible line chart	93.75% (45)	25.56	15.5
Non-accessible line chart	87.50% (42)	23.48	15.0

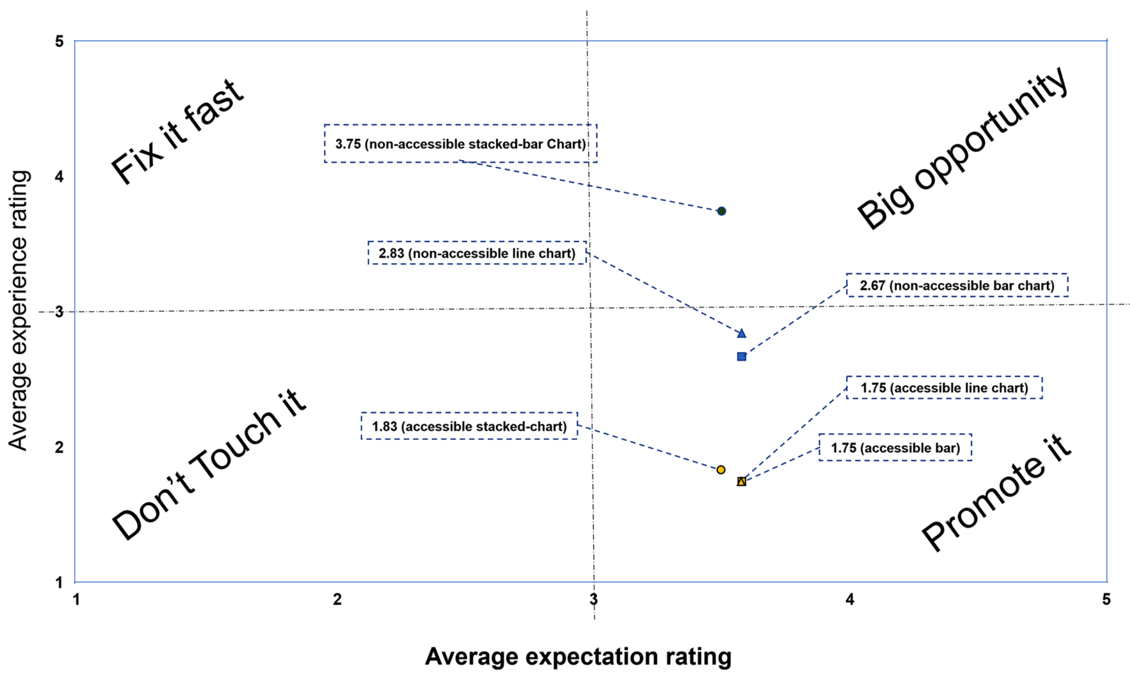


Fig. 3 Measure of expectations with accessible and non-accessible charts

Table 7 shows all users' average percentage of solved tasks for the accessible and non-accessible versions of each chart (effectiveness), all users' average efficiency in seconds by type of chart and version and, finally, the median value.

The accessible version of the stacked bar chart and the line chart present greater effectiveness (88.33% and 93.75%) than the non-accessible versions (81.67% and 87.50%). On the other hand, the non-accessible bar chart shows a higher effectiveness than the accessible one (98.33% vs. 91.67%).

In terms of efficiency, the accessible versions of the bar chart and the stacked bar chart are superior to the non-accessible versions (21.3 and 23.2 s vs. 44.58 and 33.38 s). However, the non-accessible version of the line chart presented greater efficiency compared to the accessible version (23.48 vs. 25.56 s).

As a relevant observation it must be considered that the floating windows of the video conferencing tool sometimes overlapped with the charts, forcing some users to spend part of the time moving them, with a negative impact on the time count.

It must also be taken into consideration that in the line chart, the time required for one of the users, far above the average, has increased the overall time count.

Related to satisfaction the metric was "measure of expectations", i.e. users were asked to rate their expected task complexity on a scale from 1 (not at all complicated) to 5 (very complicated), and after completing the task, they were also asked to rate the actual complexity they experienced using the same 1 to 5 scale.

The comparison between expectations and experience [93] is clearly favorable, being most charts in the quadrant of "promote-it" (Fig. 3), meaning that the users got better results than expected and as such, were very satisfied, while in the case of non-accessible charts the comparison

Table 8 Expected satisfaction by chart type

Chart type	Expected satisfaction (1 to 5, 5 more difficult)
Bar chart	3.58
Stacked bar chart	3.50
Line chart	3.58

Table 9 Experienced satisfaction by chart type

Chart type	Experienced satisfaction (1 to 5, 5 more difficult)
Accessible bar chart	1.75
Non-accessible bar chart	2.67
Accessible stacked bar chart	1.83
Non-accessible stacked bar chart	3.75
Accessible line chart	1.75
Non-accessible line chart	2.83

between expectations and experience puts the experience in the quadrant of "big opportunity" (Fig. 3), meaning that the expectations are so low that small improvements can bring great results. Tables 8 and 9 show the expected and the experienced satisfaction by chart type, respectively.

When asked which version of each chart users found easier to use, most users preferred the accessible version over the non-accessible one (86.11% vs. 13.89%), reinforcing the satisfaction results, except for user 7 (stacked bar chart), user 8 (line chart), user 10 (bar and line charts), and user 11 (both bar charts).

> "Interacting with the charts (referring to accessible charts) has allowed me to obtain the data you requested me more quickly. In the case of those that are not accessible, I have had to make an additional effort" (user 5).

4.2 Observations

In this section, we offer a comprehensive explanation of results, strategies, and difficulties experienced by users. This information is not readily available in existing literature but proves invaluable for designing more specialized tests or categorizing users into specific groups for more relevant comparisons. Additionally, this in-depth understanding will greatly inform the design of accessible charts and aid in the development of effective solutions or approaches.

4.2.1 Observations by user

Given the significant diversity in profiles, contexts of use, preferences, and assistive technologies employed by the users, Table 10 presents the details of the observations of users' interactions with the charts throughout the test. Strategies are marked-up with the style subtle-emphasis and difficulties marked-up with emphasis style, to facilitate skim reading through the table.

4.2.2 Other observations

The use of color (H10) in the non-accessible versions of the three charts has been a barrier for users 6, 8 and 9. In these three cases, the accessible version, with greater contrast and with patterns as an alternative to color, has allowed them to complete the tasks in a shorter amount of time. However, some users preferred the use of colors instead of the white, black, and grey version of the accessible version (1, 2 and 7). In particular, user 11 has highlighted that the absence of color and the interactivity (H17) implemented had not benefited him. The same user also highlighted that the use of patterns confuses him. User 6, affected by CVD, and user 9, with achromatopsia, hold a completely contrasting viewpoint on this matter.

> "The interactivity of the chart facilitates its use, but it is better in color than in black and white" (user 1).
> "I prefer colors than textures or patterns" (user 3).
> "Due to the type of vision loss, I have, the color suits me very well" (user 11).
> "As I have achromatopsia, I find it very useful that the bars have patterns to better distinguish them" (user 9).
> "In the case of stacked bar charts, it is essential to have high contrast colors to be able to differentiate between the two sections. Patterns seem a good solution to me." (user 6).

Among the magnification options (H14), we find two differentiated strategies depending on the user: (a) use of the operating system's magnifying glass or screen magnifier; (b) use of the browser zoom. In the first case, resizing means losing certain parts of the chart and, with them, important information to carry out the proposed tasks. This situation has been the case for users 1 and 2 (could not locate the legend) (H2). In those cases, when the task involves making a comparison between data, they are forced to memorize the first value and look for the second by scrolling through the screen. In the second case (magnifying with the web browser), the accessible version adjusts its size to the window width after applying the zoom, allowing users to see the entire chart on the screen, but not certain elements that accompany it, such as the table with the data source (H6) or the legend (H2). Thus, the accessible versions facilitate

Table 10 Qualitative observations per user and chart

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 1 Browser's zoom and Windows high contrast mode	Bar chart	Effectiveness: the user successfully answers all the questions posed with both charts Efficiency: During task 5, here is an observable increase in the time required to complete the task. In this instance, the user takes longer because he reads the values of the tooltips instead of comparing the length of the bars	Non-accessible version: when the user opens the chart, he reviews the entire contents of the page, including the chart and data table. It also adjusts the zoom level to 150% and brings his face closer to the screen Upon listening to the first task, he asks the moderator if he can use the data table In both the first and second tasks, the user scrolls to the bottom area of the chart to consult the caption. Throughout all tasks, the user reviews the chart by following the bars with the mouse, as well as examining the axes Accessible version: in the first task, the user hovers the mouse pointer over the bars, triggering the tooltip, and zooms in on the screen to read the data Similar to the previous case, the user follows the bars with the mouse, but in this instance, he constantly uses the tooltips	The user found it easier to complete tasks with the accessible chart, primarily due to the helpful tooltips. However, he expressed a preference for the use of color in the bars, in contrast to the black and white appearance of the accessible version

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 2 Windows magnifier and high contrast mode. Handheld Magnifying Glass	Bar chart	Effectiveness: In the non-accessible version, tasks 2 to 5 were answered correctly, but the first task was not. In the accessible version, tasks 1 to 4 were answered correctly, but not the fifth one Efficiency: In all cases, it took longer to complete the tasks with the non-accessible version. Notably, for the first two tasks it took significantly longer with the non-accessible versions (267.35% and 323.53% longer, respectively)	Non-accessible version: After receiving the task, the user expresses confusion about the correspondence of each color (legend) to specific elements. The moderator advises the user to scroll down the page to view the legend. The user approaches the screen and promptly utilizes a hand-held magnifying glass. Throughout all tasks, the user reviews the chart by following the bars and the x-axis with the mouse. Starting from task 3, the user maintains the zoom level at 110% Accessible version: Upon opening the chart, the user thoroughly reviews it and scrolls to view all the bars. Simultaneously, they hover the mouse pointer over the bars and inspect the tooltips. He sets a zoom level that allows him to view the entire chart on the screen. Initially, the user uses the order of the bars to interpret the years. Later, he observes the legend as well as the same information in the tooltips. For all tasks, the user relies on the chart rather than the data table	The user mentions that he found it relatively easy to complete the tasks with both versions of the chart, though it was slightly easier with the accessible version

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 3 Windows magnifier	Bar chart	Effectiveness: The user provides correct answers to all the questions with both charts Efficiency: In task 3 of the accessible version, the user needed more time due to interference from the Windows magnifying glass' window. Similarly, in task 5 of the accessible version, the user required additional time because certain values disappeared from the screen when the browser zoomed in	Non-accessible version: Upon opening the chart, the user thoroughly examines the entire page. Upon hearing the first task, he expresses the need to see the small values and zooms in by 200% using the Windows magnifier glass. He also approaches the screen closely. Throughout all tasks, he utilizes the chart to complete them, consults the legend, and navigates by following the bars with the mouse pointer Accessible version: He zooms in by 200% using the Windows magnifying glass. After hearing the first task, he briefly closes the magnifying glass to adjust the videoconferencing tool window. For all tasks, he relies on the chart to complete them, consults the legend, and primarily use a comparative approach, comparing the length of the bars and consulting the tooltips to solve the tasks	The user mentions that he found it relatively easy to complete the tasks with both versions of the chart, although the accessible version was easier due to the labeled values of bars and the presence of tooltips. However, he expresses a preference for color bars over the use of patterns
User 4 Handheld Magnifying Glass	Bar chart	Effectiveness: the user provides correct answers to all the questions with both charts Efficiency: in all cases (except for task 3 where the time taken was similar for both versions) it took longer to complete the tasks with the non-accessible version. Notably, for the first two tasks the non-accessible versions required significantly more time (964.71% and 350% longer, respectively)	Non-accessible version: The user initially employs a hand magnifying glass but struggles to see the Y-axis category names. He subsequently increases the browser zoom to 133% and then to 150%. Starting from task 2, the user set the browser zoom to 200%. Throughout all tasks, he relies on the chart rather than the data table Accessible version: The user initially sets the browser zoom to 110% and then to 133%. Later, he reduces it to 100%. To complete all tasks, he primarily uses the chart and interprets the values based on the order of the bars, rather than referring to the legend	The user found the non-accessible version to be quite complicated, whereas he found the accessible version much easier to use

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 5 Browser's zoom	Bar chart	Effectiveness: The user provides correct answers to all the questions with both charts Efficiency: In all cases, it took longer to complete the tasks with the non-accessible version, except in task 4, where the user's efficiency improved due to learning effects	Non-accessible version: initially she examines the chart and the table headings. After hearing the first task, she navigates to the data table and then reviews the chart again. She answers the questions using the chart but cross-checks her answers with the table. She mentions that the axis titles have poor contrast, which is why she relies on the table to verify her responses. In all tasks, she primarily uses the chart but references the table for the first three tasks Accessible version: Upon opening the chart, the video conferencing tool window partially obscures it. The moderator advises her to move the window for better visibility. She uses the labeled value of each bar for all tasks. In cases where the value is not visible, she resorts to comparing the length of the bars	She described the non-accessible version as neither particularly easy nor difficult. Conversely, she found the accessible version notably easier, attributing this ease to the higher contrast, the presence of data labels and the availability of tooltips

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 6 Zoom and inverted colors in MacOS	Bar chart	Effectiveness: The user provides correct answers to all questions with both charts Efficiency: In all cases the user requires nearly twice as much time to solve the tasks with the non-accessible chart. Task 1, in particular, shows a time increase of 143.75%	Non-accessible version: the user employs the inverted color mode to read the text. He zooms in nearly to the maximum and moves the mouse cursor along the X-axis while the moderator asks him the questions. Throughout the test, he adjusts the window of the videoconferencing tool, which appears above the legend. However, He does not locate the legend until task 2. The user mentions a preference for consulting the data table. To solve the tasks, he relies on both the chart and the table. The user needed to approach the screen closely to solve the tasks Accessible version: In this case, the user does not activate the inverted color mode. He uses a lower zoom level than the employed with the non-accessible chart. The user examines the chart, the legend, and the data table. Again, he must adjust the window of the videoconferencing tool. During task 1, he initially looks for the answer in the data table and then verifies it with the chart. After realizing that the bars are labeled with values and have tooltips, he begins answering using the chart and cross-checking some answers with the table	He found the non-accessible version to be quite complicated, while the accessible version was straightforward and more user-friendly
User 7 Windows magnifier and high contrast mode. Handheld Magnifying Glass	Bar chart	Effectiveness: The user provides correct answers to all the questions with both charts Efficiency: In tasks 1 and 3, the user took longer to respond with the non-accessible version, while in tasks 2, 4 and 5, it took longer with the accessible one. This can be attributed to two reasons: (a) in task 2, the user directly used the data table instead of the non-accessible chart; (b) in tasks 4 and 5, after increasing the zoom level of the browser, some data labels of the accessible chart disappeared	Non-accessible version: After hearing the first task, the user uses a hand-held magnifying glass to review the Y-axis labels and the chart title. While searching for the legend, he discovers the data table and uses it to solve all the tasks Accessible version: Upon opening the chart, the user notices the values at the end of each bar. He continues to utilize the hand magnifier glass to complete the tasks. In task 5, when one of the values disappears, he relies on comparing the bars to provide an answer	The user found the accessible version easier to work with, although he noted that in some bars, the data labels did not appear. The user also mentioned that he might have found it easier after using the non-accessible version initially

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 8 Windows magnifier	Bar chart	Effectiveness: the user provides correct answers to all questions with both charts Efficiency: in all cases, the user needed more time to complete the tasks with the non-accessible chart. In tasks 1 and 2, the increase in time was 52.11% and 339.29%, respectively	Non-accessible version: The user uses the Windows magnifier glass at 500% and approaches the monitor closely. Initially, he mentions having difficulty differentiating colors. He also explains that reading the Y-axis labels is challenging. Additionally, he has trouble finding the legend. In task 2 he discovers the table and asks the facilitator if it corresponds to the chart. From then on, he consistently uses the table Accessible version: She continues using the Windows magnifier glass at 500%. She explains that she can see the Y-axis labels better with this version. In some tasks, she resorts to using the data table because the chart is partially obscured by the video conferencing tool window. She comments that, in general, she always finds it easier to use the table	She found the accessible version easier to use
User 9 Browser 's zoom	Bar chart	Effectiveness: the user provided correct answers to all the questions with both charts Efficiency: In all cases the user took more time to complete the tasks with the non-accessible chart. In task 2, the time required was 469.44% longer with the non-accessible chart	Non-accessible version: Initially, the user reads the chart's title and mentions that she sees three colors per category, but that she finds them practically identical. She identifies the gray color (central bar) as helping her differentiate between the other two. She struggles to perceive the legend correctly. In task 2, she discovers the data table and begins using it to solve the tasks Accessible version: Right from the start, she relies on the data table to complete all tasks	She found the accessible version easier to consult. Although she needed to use the table for some tasks, she mentioned that the colors and textures of the accessible version were easier to interpret

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 10 Windows magnifier and browser's zoom	Bar chart	Effectiveness: The user provides correct answers to all the questions with both charts Efficiency: The user took less time to solve tasks 1, 3 and 4 with the non-accessible version. Task 2 took the same amount of time with both charts. Task 5 took less time with the accessible version. The user mentioned that the interactive charts confused him, which influenced the time required to solve the tasks	Non-accessible version: the user sets the zoom level of the Windows magnifier between 200 and 250%. Initially, the user reviews the chart in general, reads the title, checks the axes titles and notices the presence of a data table. All tasks are solved by comparing the length of the bars. The user does not seem to have trouble differentiating the colors or interpreting the legend Accessible version: the user sets the zoom level of the Windows magnifier between 200 and 250%. In the first task, horizontal scrolling was required, and the user has to scroll multiple times from left to right to view the labels on the Y-axis. Although the user observes that placing the mouse pointer over the bars triggers tooltip with all the information, the user continues to scroll horizontally to verify the category to which each bar belongs	The user prefers the non-accessible version due to the color selection. He also founds the subtle color change when the mouse cursor passes over the bar in the accessible version confusing
User 11 Browser's zoom	Bar chart	Effectiveness: the user provides correct answers to all the questions with both charts Efficiency: The user required more time to complete tasks with the non-accessible charts, except in task 4 where he needed only one second more with the accessible one	Non-accessible version: The user maintains a zoom level of 100% and solves all tasks by comparing the length of the bars Accessible version: the user also keeps the zoom level at 100% and solves all tasks by comparing the length of the bars. However, she mentions feeling confused by the color scheme used in the accessible chart (black/gray). On the other hand, though she understood the potential benefits of interactivity in certain situations	The user found both versions of the charts to be straightforward, but he prefers the color version (the non-accessible one) because it made him feel more comfortable

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 12 Windows magnifier and high contrast mode. Screen reader	Bar chart	Effectiveness: the user provides correct answers to all the questions with both charts Efficiency: the user requires more time to complete all tasks with the non-accessible charts. The most significant differences are observed in tasks 1 (43 s vs. 12 s) and 2 (19 s vs. 4 s)	Non-accessible version: the user employs the Windows magnifying glass and adjusts the zoom level, ranging from 100 to 150%, depending on the task. All tasks are solved by comparing the length of the bars and referring to the legend Accessible version: the user utilizes the Windows magnifying glass and varies the zoom level, ranging from 100 to 150%, based on the task. All tasks are completed by comparing the length of the bars and referencing both the legend and the tooltips	The user reports that solving the tasks with the non-accessible chart was quite complicated, while those with the accessible chart were very easy
User 1 Browser's zoom and Windows high contrast mode	Stacked bar chart	Effectiveness: The user provides correct answers to all the questions with both charts, except for task 1 with the non-accessible version Efficiency: In tasks 1, 2, and 4, the user took longer with the non-accessible version. However, in tasks 3 and 5, it took a little longer with the accessible version. In the case of task 3, this was due to the video conferencing tool window which caused some inconvenience and required adjustment	Non-accessible version: When the user opens the chart, he set the browser zoom to 200% and review the chart (not the table). To solve the tasks, he uses the chart and follows the bars with the mouse pointer. Throughout, he approaches the computer screen very closely Accessible version: To solve tasks 1 and 2, the user uses the tooltips. For tasks 3 and 4, he reviews the data label and the tooltips. For task 5 he looks at the bars and positions the mouse pointer on the bar he selects as the answer. Throughout, he approaches the computer screen very closely	He found the accessible version easier to use because of its interactivity, which includes data labels, hover effects and tooltips

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 2 Windows magnifier and high contrast mode. Handheld Magnifying Glass	Stacked bar chart	Effectiveness: the user answered task 3 correctly with the non-accessible version. With the accessible version, the user answered tasks 2, 3 and 5 correctly but answered tasks 1 and 4 incorrectly Efficiency: in all cases, the user took longer to complete the tasks with the non-accessible version, except for task 4	Non-accessible version: Initially, the user reviews the entire chart without scrolling to the table. The user sets the browser zoom to 120%. Tasks are completed by scrolling the chart, consulting the legend, and guiding the mouse pointer across the axes Accessible version: Initially, the user reviews the chart and reads the caption. In the first task, he maintains a 120% zoom level, causing some data labels to be missing, leading to misinterpretations. The user also mentions difficulty differentiating bar sections due to the gray/black combination. In task 2, the user zooms out to 100% and all missing values reappear. The user encounters issues with the video conferencing tool window, which the moderator helps resolve. All tasks are completed using the chart without consulting the table, and the user frequently approaches the screen	The user found the accessible version easier to use overall, although he expressed a preference for a gray /red combination
User 3 Windows magnifier	Stacked bar chart	Effectiveness: The user incorrectly answered tasks 1 and 2 with the non-accessible version, but correctly answered all the questions with the accessible version Efficiency: The user takes more time to solve all the tasks with the non-accessible version, with a 266.67% increase in time compared to the accessible version for task 1	Non-accessible version: The user sets the Windows magnifying glass to 200% and locates the legend. He completes all tasks using only the chart Accessible version: After reviewing the chart, the user sets the zoom to 100%. To complete all tasks, he looks at the data labels on the bars of the chart. The user frequently approaches the screen	He found the accessible version easier to use. In the non-accessible version of the stacked bar chart, it was difficult to distinguish between the two sections of each bar

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 4 Handheld Magnifying Glass	Stacked bar chart	Effectiveness: The user answered tasks 1 and 4 incorrectly in the non-accessible version. In the accessible version, the user answered tasks 2 and 3 incorrectly Efficiency: In all cases, the user took longer to complete the tasks with the non-accessible version, except for task 2. In task 2 of the accessible version, the user initially consulted the chart and then the table, while in the non-accessible version, he looked for the answer directly in the table	Non-accessible version: Upon opening the chart, the user adjusts the browser zoom level to 150% and uses a hand-held magnifying glass to examine the values in the table. For the first task, he relies solely on the chart, guided by the axes and bar sizes. Starting from task 2, he switches to using the table Accessible version: After reviewing the chart, the user sets the browser zoom to 133%. In the first task, he inspects the data labels of the bars. For task 2, he reduces the browser zoom to 120% and finds the answer in the data table. From task 3 onward, he primarily uses the chart and occasionally checks the axes using the hand-held magnifying glass	The user found the accessible version easier to use and, at times, had to rely on the table when using the non-accessible version
User 5 Browser's zoom	Stacked bar chart	Effectiveness: the user correctly answers all the questions with both charts, except for task 2 with the non-accessible version Efficiency: In all cases, the user took longer to complete the tasks with the non-accessible version. The difference in completion times was most significant in task 1 (472.73%), task 3 (89.47%) and task 4 (118.52%)	Non-accessible version: the user consults the data table when the question involves the partial interpretation of each bar, and the chart when it involves the global interpretation of each stacked bar. In task 4, she looks at the y-axis and follows the line to compare the bars. She needs to get closer to the screen constantly Accessible version**:** Throughout the tasks, she reviews the chart to complete them and is guided by the size of each bar, the colors, and the data labels at the top of each bar. She needs to get closer to the screen constantly	She found the accessible version easier to use, to the extent that she had to resort to the table on some occasions when using the non-accessible version

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 6 Zoom and inverted colors in MacOS	Stacked bar chart	Effectiveness: The user correctly answers all the questions with both charts Efficiency: In all cases, the user took longer to solve the tasks with the non-accessible version, except for task 3, in which he spent a few seconds reading the caption. The difference between versions is significant in terms of efficiency in tasks 1(73.33%); 2: (112.73%); and 4: (108.33%)	Non-accessible version: After reviewing the chart, the user turned off the inverted color mode and tried different zoom settings. Whenever reading text, the user approached the screen. After hearing the first task, the user turned the inverted color mode back on and read the title of the chart. He applied the operating system zoom to read the X-axis labels and browsed the answers in the data table. For tasks that required partial interpretation of the bars, the user used the table. When tasks required global interpretation of each bar, the user consulted the chart and verified the answer with the table. For some tasks, the user followed the axes with his finger. The inverted color mode was activated when reading text and deactivated when checking the bars Accessible version: After reviewing the chart, the user looked at the table and tooltips. With the inverted color mode, it was almost impossible to differentiate the two sections of each bar. After deactivating it, the difference between the two sections improved, but the user still could not distinguish them correctly. He used the tooltips to solve the tasks and also read the caption and checked the table to verify the answers	He found the accessible version easier to consult, while the non-accessible version was very complicated

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 7 Windows magnifier and high contrast mode. Handheld Magnifying Glass	Stacked bar chart	Effectiveness: the user correctly answered all the questions with both charts, except for task 1 with the accessible version Efficiency: In all cases, the user took longer to complete the tasks with the non-accessible version, except for task 2, where he was faster with the non-accessible version when directly browsing the table, which he did not do with the accessible version. Additionally, in the accessible version, he needed to use the handheld magnifying glass, which was unnecessary with the table	Non-accessible version: Initially, he reads the chart title using a hand-held magnifying glass and thoroughly examines the entire page, paying particular attention to the colors of each section of the bars. In task 1, he starts by using the chart, but quickly switches to the table to find the answer. In task 2, he directly consults the table, and from task 3 onwards, he reverts to using the chart as his primary reference. Throughout, he consistently employs the hand-held magnifying glass and frequently consults the data table Accessible version: Initially, the user looks for the legend to identify the corresponding colors. Initially, he finds it challenging to differentiate between colors, although the contrast eventually proves sufficient for him. He also checks the chart. Throughout, he primarily uses the chart to answer the tasks, aided by a hand-held magnifying glass to read the X-axis labels and the data labels on the bars. He also compares the lengths of the bars to solve some tasks	He found both versions equally challenging but prefers the non-accessible version because the use of color makes it easier for him to distinguish between the marks

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 8 Windows magnifier	Stacked bar chart	Effectiveness: The user correctly answered all the questions with both charts Efficiency: In tasks 2, 4 and 5, the user required more time to answer the questions with the non-accessible version. In tasks 1 and 3, she needed more time with the accessible version. In task 1, this was because he used the data table directly with the non-accessible version, while with the accessible version, she consulted the chart using the Windows magnifying glass at 500%, which required multiple moves to view the necessary elements. In task 3, the videoconferencing tool's window interfered with the chart, causing some delay as he had to reposition it	Non-accessible version: Initially, she examines the entire page containing the chart. Then, she sets the Windows magnifier glass to 500% and approaches the screen. In tasks 1 and 2, she directly uses the data table. Starting from task 3, she relies on the chart. Task 4 sees her return to using the table due to some difficulty understanding the question, which partly explains the significant time difference between versions (80 s with the non-accessible chart and 30 s with the accessible one). In task 5 she consults both the chart and the table Accessible version: the user maintains the same zoom level as in the previous version. Initially, she reviews the entire chart and mentions that she could see the axis labels better with the previous non-accessible version. She also notes that reading text vertically poses a significant barrier for her. In task 3, the video conferencing tool window overlaps some of the bars and interferes with the task. In task 4, she uses the Y-axis as a reference and follows a line with the mouse pointer	She found the accessible version easier to use
User 9 Browser's zoom	Stacked bar chart	Effectiveness: the user answered all the questions correctly with both charts Efficiency: in most cases, the user took longer to complete the tasks with the non-accessible version, except for task 1, in where she initially misunderstood the order of the values	Non-accessible version: Initially, the user examines the entire chart. However, the user expresses difficulty with this type of bar chart and decides to rely solely on the data table for all tasks. In task 4, he briefly refers to the chart to confirm the answer Accessible version: Upon opening the chart, the user reviews its content and reads the caption. For all tasks, he uses the data table instead of the chart	She found the non-accessible version to be quite complicated, while she found the accessible version easier to consult

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 10 Windows magnifier and browser's zoom	Stacked bar chart	Effectiveness: The user correctly answers all the questions asked with both charts, except for tasks 2 and 4 with the accessible version Efficiency: In tasks 2, 4 and 5 the user needed more time with the non-accessible version. However, in tasks 1 and 3, he required more time with the accessible version (2 and 5 s, respectively). In these cases, the user positively noted the size and resolution of the numerical values, as well as the selected colors	Non-accessible version: The user sets the Windows magnifier zoom level between 200 and 250%. Initially, the user reviews the entire chart, reading the title and axes, and notices the availability of a data table is available. The user solves all tasks by comparing the length of the bars. There don't appear to be any issues with differentiating colors or interpreting the legend Accessible version: The user sets the Windows magnifier zoom level between 200 and 250%. The user solves all tasks by comparing the length of the bars. When it is necessary to compare the entire series, the user reduces the zoom level to have a panoramic view	The user prefers the non-accessible version due to the color selection. He also finds the subtle color change when the mouse cursor passes over the bar confusing in the accessible version
User 11 Browser's zoom	Stacked bar chart	Effectiveness: the user correctly answers all the questions asked with both charts Efficiency: in all cases, the user took longer to solve the tasks with the non-accessible version. The most significant differences in time spent are observed in tasks 1 (15 s vs. 6 s), 2 (13 s vs. 8 s), and 4 (14 s vs. 6 s)	Non-accessible version: the user maintains a zoom level of 100%. Task 1 requires consulting the table, while the remaining tasks are solved by referring to the chart Accessible version: the user maintains a zoom level of 100%. All the tasks are solved by consulting the chart	She found the non-accessible chart to be overly complicated. In contrast, she appreciated the interactive features, such as tooltips, in the accessible version
User 12 Windows magnifier and high contrast mode. Screen reader	Stacked bar chart	Effectiveness: The user correctly answers all the questions asked with both charts, except task 1 with the non-accessible version Efficiency: The user took longer to solve the tasks with the non-accessible version in tasks 1 (with a ten-second difference) and 2. On the other hand, the user took longer to solve the tasks with the accessible version in tasks 3, 4 and 5, but the difference were only 1 s (tasks 3 and 4) and 2 s (task 5)	Non-accessible version: The user uses the Windows magnifying glass and changes the zoom level according to the task, ranging from 100 to 150%. All tasks are solved by comparing the length of the bars and checking the legend Accessible version: with this chart, the user does not need to magnify the screen with the Windows magnifier. All tasks are solved by comparing the length of the bars and checking the legend and the tooltips	The user states that she found solving the tasks with the non-accessible chart quite complicated, while completing them with the accessible chart was very easy

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 1 Browser's zoom and Windows high contrast mode	Line chart	Effectiveness: the user correctly answers all the questions asked with both charts Efficiency: in tasks 1, 4 and 5, the user needed more time with the non-accessible version. However, in tasks 2 and 3, the user required more time with the accessible version for two reasons: (a) the distance between the points of the lines was smaller necessitating more time to compare them; (b) he spent additional time verifying the answer with the tooltips before verbalizing it	Non-accessible version: the user applies a 150% zoom with the browser and approaches the screen. First, he reads the legend and examines the entire chart. To solve the tasks, he follows the lines with the mouse pointer and constantly consults the legend Accessible version: first, he scrolls until he finds the legend. During the process, he notices that tooltips appear when hovering over the dots. The user sets the browser zoom to 125% and approaches the screen. To solve all the tasks, he positions the cursor over the point and reads the tooltips	He found the accessible version easier to consult
User 2 Windows magnifier and high contrast mode. Handheld Magnifying Glass	Line chart	Effectiveness: the user correctly answers all the questions asked with both charts, except for task 1 and 2 with the non-accessible version Efficiency: The user required more time to complete tasks with the non-accessible version in all cases except for task 3. Like user 1, this can be attributed to two reasons: (a) the smaller distance between the points of the lines, requiring more time for comparison; (b) spending additional time verifying the answer with tooltips before verbalizing it	Non-accessible version: Initially, he reviews the entire page and adjusts the browser zoom to 125%. He examines the caption and title. For tasks 1 and 2, he tracks the lines and axes to answer the questions. Task 4 presents a particular challenge due to the close proximity of the two lines, and he frequently refers to the legend before answering Accessible version: He begins by hovering the mouse pointer over the chart to check for tooltips. In task 1, he consults the legend and, although he can distinguish the lines, he appears to use tooltip information to answer the task. Starting from task 3, he relies exclusively on tooltips to address the questions	He found the non-accessible version to be rather complicated, while the accessible version was easier to use

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 3 Windows magnifier	Line chart	Effectiveness: the user correctly answered all the questions asked with both charts Efficiency: in tasks 1 and 4, the user required more time to complete the tasks with the non-accessible chart. Conversely, in tasks 2, 3 and 5 it took longer with the accessible version. Notably, in task 5, the user needed 94.74% more time due to a lack of understanding of the question	Non-accessible version: Initially, the user sets the Windows magnifier glass to 200% and reads the chart title, exploring the entire content on the screen, including the X-axis labels and legend. In task 1, he relies on legend to identify each airport. However, in task 4, he encounters difficulty distinguishing between two closely spaced lines. For all tasks, he tracks the lines using the mouse pointer to find the answers Accessible version: At first, the user examines the entire chart. In task 1, he consults the legend to associate each line with its corresponding airport. Starting from task 3, he utilizes the tooltips to complete the tasks	He found the accessible version easier to work with. In the non-accessible version, he encountered difficulty distinguishing between the lines
User 4 Handheld Magnifying Glass	Line chart	Effectiveness: the user answered task 4 incorrectly with the non-accessible version and tasks 1 and 3 incorrectly with the accessible version Efficiency: In tasks 1 and 2 the user required more time with the non-accessible version. In tasks 3 and 4, more time was needed with the accessible version. Finally, in task 5, the user required the same amount of time in both versions. The increase in time for tasks 3 and 4 with the accessible version can be attributed to the user's initial hesitation to interact with the chart, instead preferring to consult the data table as in the non-accessible version	Non-accessible version**:** Initially, the user looks at the chart, and then sets the browser zoom to 120%. During task 1, increases the zoom to 150% but struggles to locate the legend. Eventually, the user solves the task using the table. For the remaining tasks, the user relies solely on the table Accessible version: in this case, the user maintains the zoom at 150%, although starting from task 3 the zoom is reduced to 133%. While reviewing the chart, the user discovers the tooltips. For all tasks, except the second one, the user utilizes the tooltips. In the second task, there were learning effects observed. Additionally, in the fourth task, the user uses the hand magnifying glass	He found the accessible version easier to consult. In the case of the non-accessible version, the user explains that he has had to consult the table for all tasks

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 5 Browser's zoom	Line chart	Effectiveness: The user correctly answers all the questions asked with both charts Efficiency: In tasks 1, 4 and 5 she needed more time with the non-accessible version, while in tasks 2 and 3, she needed more time with the accessible one. The increase in time in tasks 3 and 4 with the accessible version is because, in the non-accessible one she directly consults the data table, while in the accessible one, she reviews the entire chart without consulting the table	Non-accessible version: First, she looks at the chart. During the first task, she informs the moderator that she will use the data table exclusively Accessible version: In tasks 1 and 2, she consults the legend to identify each line. In all tasks, she uses the chart and does not seem to have great difficulty in differentiating the lines	She found the accessible version easier to consult. The user explains that without the data table, he would have had a hard time solving the tasks of the non-accessible version
User 6 Zoom and inverted colors in MacOS	Line chart	Effectiveness: the user correctly answers all the questions asked with both charts Efficiency: in tasks 1, 2 and 5, the user needed more time with the non-accessible version. The most significant increase is in task 5 with a 178.33% increase in time. In tasks 3 and 4, the user needed more time with the accessible version (165.22% and 176.47%, respectively). This is because when the zoom is applied, the tooltips obscure practically the entire chart, making it difficult to see the lines	Non-accessible version: the user activates the inverted color mode and the macOS screen magnifier. First, he reviews the chart and reads the title. In task 1, he finds the legend and deactivates the inverted color mode. He then turns it back on to read the title and X-axis labels. The user states that he sees the text better with the inverted color mode, but that the colors are better differentiated without it. In task 2, he consults the chart and verifies the answer with the table. Task 5 is particularly difficult for him, and he ends up using the table Accessible version: with the color mode inverted, he reviews the chart and table and also reads the caption. In task 1, he reviews the legend and the chart. In task 2, he consults the tooltips and verifies the answer with the table. In task 3, he uses the chart and verifies the answer with the table. In task 4, the tooltips interfere when he is following the lines with the mouse pointer, and he decides to use the table. In task 5, he starts by consulting the chart, but finally uses the table	He found the accessible version easier to consult and appreciate the ability to resize the image without losing definition. However, he did not like the inability to deactivate the tooltips

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 7 Windows magnifier and high contrast mode. Handheld Magnifying Glass	Line chart	Effectiveness: the user correctly answers all the questions asked with both charts Efficiency: In tasks 1, 4 and 5, the user required more time with the non-accessible version. However, in tasks 2 and 3, the user needed more time with the accessible version. This was because the distance between the points of the lines was smaller, requiring more time for comparison	Non-accessible version: when opening the chart, the user verbalizes the colors of each line. In the first task, the user consults the legend and reads the X-axis title using a hand-held magnifying glass. In the second task, there were observed learning effects. For the subsequent tasks, the user continues to use the hand magnifier to follow the lines and axes Accessible version: After opening the chart, the user reviews the legend to differentiate the lines of the chart. For most of the tasks, the user uses a hand magnifying glass to solve them	He found the accessible version somewhat easier to use
User 8 Windows magnifier	Line chart	Effectiveness: the user correctly answers all the questions asked with both charts, except task 3 with the accessible version Efficiency: In tasks 4 and 5, she needs more time to solve the tasks with the non-accessible version. However, in tasks 1, 2 and 3 (with a significant increase of 1120% in task 3), she requires more time with the accessible version. This is because with the zoom at 500%, she can only see a very limited portion of the screen, which is further obscured by the tooltips. Additionally, in task 3, the user appears to be getting tired	Non-accessible version: Upon viewing the chart, she notices that the Y-axis values are very small and pixelated. Consequently, she looks at the data table and increases the Windows magnifying glass to 500%. In task 1, she successfully locates the legend to identify each line. However, in tasks 2 and 3, she relies on the data table for answers. For task 4, she initially consults the chart, but ultimately resorts to the table. In task 5, she attempts to use the chart again but struggles due to the high zoom level, leading her to return to the table Accessible version: In this instance, she maintains the Windows magnifying glass at 500%. In task 1, she encounters interference from the video conferencing tool window, which she must relocate. During task 2, she starts by consulting the chart, but finds the tooltips bothersome, prompting her to switch to the table. In task 3, she expresses fatigue. Finally, in tasks 4 and 5, she relies on the table exclusively	She found the non-accessible version easier to consult

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 9 Browser's zoom	Line chart	Effectiveness: the user correctly answers all the questions asked with both charts, except for task 1 with the non-accessible version Efficiency: in tasks 1, 2, and 4, the user takes longer with the non-accessible version. In task 3, the user takes longer with the accessible version initially due to a mistake and its rectification. Finally, in task 5, the user takes the same amount of time with both versions	Non-accessible version: the user mentions that she can easily see both the chart and the data table. She consistently uses the data table to respond while moving closer to the computer screen Accessible version: the user reports that she can easily see both the chart and the data table. Additionally, she reads the caption. Like the non-accessible version, she relies on the data table for her responses and adjusts her proximity to the computer screen as needed	She found the accessible version easier to work with
User 10 Windows magnifier and browser's zoom	Line chart	Effectiveness: the user correctly answered all the questions asked with both charts, except for task 4 with the non-accessible version Efficiency: the user needed more time with the accessible version in all tasks except for task 4. The main reason for this is that the zoom level applied to the accessible version caused part of the chart to be off the screen, leading the user to scroll constantly to compare and review values	Non-accessible version: the user sets the zoom level of the Windows magnifier between 200 and 250%. The user solves all tasks by comparing the height of the points on each line. He does not seem to have trouble differentiating the colors or interpreting the legend Accessible version: The user must reduce the zoom level to see the entire chart on the screen. The user mentions that if both lines were the same (one is continuous and the other is dotted), it would be very difficult to differentiate between them. He solves all tasks using the chart only, without consulting the table	The user prefers the non-accessible version because, after zooming in, a part of the chart has been left out of his screen, requiring more movements to compare data. Additionally, the user mentioned that the subtle change of color when the mouse cursor passes over the bar is confusing
User 11 Browser's zoom	Line chart	Effectiveness: the user correctly answers all the questions asked with both charts Efficiency: the user needed more time with the accessible version in all tasks except task 3. Task 2 required the same amount of time in both versions. In task 1, he took twice as long with the non-accessible version (14 s vs. 7 s)	Non-accessible version: the user maintains a zoom level of 100%. She consults the charts to solve all tasks, except for tasks 4 and 5, where she needs to refer to the data table Accessible version: the user also maintains a zoom level at 100%. All tasks are completed by consulting the chart	In this case, she found it easier to use the accessible chart because it includes a complete grid

Table 10 (continued)

User	Chart	Effectiveness and efficiency	Observations	Satisfaction
User 12 Windows magnifier and high contrast mode. Screen reader	Line chart	Effectiveness: the user correctly answered all the questions asked with both charts, except for task 4 with the non-accessible version Efficiency: The user needed the same amount of time for both versions in task 2. For the remaining tasks, she completed them more quickly with the non-accessible version, except for task 4 where there was a difference of 2 to 25 s in completion time	Non-accessible version: the user employs the Windows magnifying glass and sets the zoom level to 125%. In task 3, she has difficulty seeing the blue line clearly and increases the zoom level to 150%. She completes all tasks by comparing the height of the points on each line and referencing the legend. It is possible that the table, which is off the screen, went unnoticed by the user Accessible version: with this chart, the user does not require screen magnification through the Windows magnifier. She resolves all tasks by comparing the height of the points on each line and referring to the tooltips	The user states that she found solving the tasks with the non-accessible chart quite complicated, while those with the accessible chart were very easy. One of the main factors was the poor definition of the non-accessible chart after zooming in

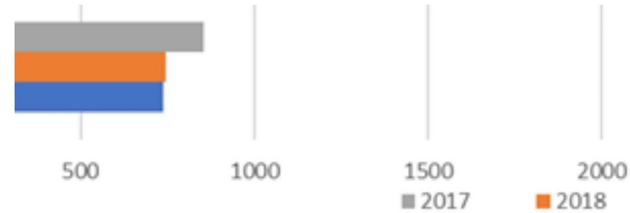


Fig. 4 Detail of the low quality of the non-accessible bar chart resized

comparisons within the chart. In this sense, tasks focused on comparing data have been performed better (more efficiently) with the accessible versions of the charts.

In the accessible versions of the charts, a tooltip functionality has been implemented to provide the value of the selected mark (bar or point) as an alternative to legends (H2). Tooltips have been useful for all users, except for user 9 who preferred to use the data table (H6). This functionality, used by almost all users, has been highly valued by users 1, 3 and 5, while users 6 and 8 in the interaction with the line chart have highlighted the fact that the tooltips obscured the chart preventing them from following the lines and seeing the marks, especially after magnifying the screen. In this case, the accessible chart does not meet the dismissible requirement associated with the success criterion 1.4.13 (Content on hover of focus) of the WCAG 2.1 [82], which could solve the difficulty mentioned by users.

> "In the case of interactive charts, you have all the information at your fingertips. You consult a point and see all the related information without looking at two places at the same time." (user 11).
> "Tooltips are nice, but with a zoom applied they cover too large a part of the chart. It would be interesting if they were optional, for example, that they only appear after clicking on them." (user 6).
> "With the second type of charts (referring to the accessible charts) I have not needed to use zoom at any time because the data is near the bars and points. I simply needed to approach a little more on the screen." (user 12).

All users have followed the strategy of following the axes (H3) and the marks with the cursor pointer.

When bitmap images (Microsoft Excel exports) were resized, the problem of their low quality was more pronounced, creating legibility problems (H12) for users 2, 3, 4, 5, 6, 7, 8 and 9 (Fig. 4). For user 2 there was even a problem differentiating the bars of the first chart due to the poor quality of the image. Specifically, he stated "it seems to be missing pixels". Insufficient contrast (H11) between the text color used by default by Microsoft Excel and the background has also been a barrier for these users even after being resized. In all these cases, the users have solved the tasks using the data table (H6) available, not the chart.

> "In the first versions (referring to the non-accessible charts) I noticed fewer sharp charts and worse contrast. The poor sharpness of the text also affected me a lot." (user 8).

In all cases, users have initially used the chart to solve the tasks. Only when they have been unable to find the answer, they have used the data table to find it, or they have used it to confirm their answers before verbalizing it (users 5, 6 and 7). User 6 was the only one to recognize that he preferred to consult the table rather than the chart in all cases. Users 7, 8 and 9 (the two last due to poor color perception) found that their efficiency improved when using the data table after the first task and have used it more frequently since then.

> "It is easier to see the data in a chart than in a table" (user 1).
> "In some cases (referring to non-accessible charts) I'd rather go to the table and deal directly with data than consult the chart, because the lines and dots are too thin for me" (user 5).
> "When I read a scientific paper (the user is a researcher in the field of genetics), I never consult the charts because they are totally inaccessible. At most, they worry about color blindness, but not about other issues that affect people with low vision. I always prefer data tables than charts". (user 6).
> "For all the questions I needed to consult the table. I always use the tables to solve this kind of situations." (user 9).

Every user, except for user 9 (who exclusively relied on the data table), frequently used legends to interpret the data (H2). Throughout the test, we observed difficulties in locating the legend when it was not positioned at the bottom of the chart or when it went off the screen due to applied zoom. In this regard, the suggestion put forth by Evergreen and Metzner [94] to label data directly, in close proximity to data points (such as on top of or beside bars and next to lines), can not only reduce cognitive load and facilitate more efficient information processing but also aid users with low vision in comprehending data series without the need for constant scrolling through the interface. We have also observed difficulty in differentiating the data series if the color was not sufficiently distinguishable (H10) or the size of the legend was not sufficient (fonts set to Calibri, 9 pt. In not-accessible charts).

In accessible versions of the bar chart and the stacked-bar chart, when a data series receives the focus (H16), the rest of the bars are displayed with less contrast to highlight the active element. This has been a barrier for user 10, who has expressed that it has confused him.

5 Discussion and limitations

The paper describes the results of an ongoing study that aims to verify a list of heuristics with users. The relatively small number of users does not allow to statistically validate the results nor to generalize them to the whole population, but the authors consider that the insights collected with this first approach are relevant and give light to barriers and priorities.

The observations made during the test heightened the authors' awareness of the diverse preferences and strategies within the low vision users' group, emphasizing the necessity to gain a deeper understanding of these interactions. Consequently, the authors have chosen to incorporate a thorough description of each user's results, strategies, and preferences in the article. This information is deemed invaluable for future research in the field.

Due to COVID lockdowns, the tests were conducted remotely, and the interface of the video conferencing platform occasionally disrupted the efficiency of users. Some users had to spend part of their time minimizing the platform's interface. This is a significant consideration for the authors and may also be a determining factor to address in future tests.

From the results obtained, we can derive some insights: a global view of the chart is very informative and users rely on it for comparative evaluations and trends; they look at it with a size that fits on screen, with not much zoom; instead the use of zoom is very important to read text, axes, labels, legends or tooltips, with many users using levels of zoom much bigger than the 200% level established by WCAG. A mechanism specific for these elements not affecting the chart should be developed and tested with users. Insight (a): a zoom option specific for text elements not affecting the chart should be devised, and it shall be flexible for zooms over 200%. Tooltips have been an important source of information but also created some problems obscuring parts of the charts. Insight (b): offer zoomable tooltips (see insight a), but callable on demand. Black and white charts did not satisfy some users, emphasizing the need to redundantly encode categories with both colors and patterns to cater to diverse user profiles and their preferences. Insight (c): offer color categories with high contrast, plus patterns, better than black and white coloring. The data table emerged as a useful alternative, particularly in non-accessible versions, enhancing task efficiency for many users who have solved the tasks by combining both the chart and table. Insight (d): always offer data in a table as a complement. On the observations many users follow axes to find a specific value in the chart. Insight

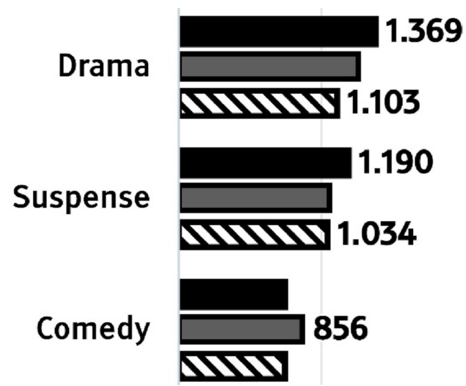


Fig. 5 Detail of the accessible bar chart showing the absence of some labels

(e): include axes in the charts as guides for locating specific points. Challenges were identified regarding the legend's position and size, and addressing these aspects is essential to eliminate potential barriers. Insight (f): provide a legend to understand the data. Ensure that its position, size, colors and contrast do not impose any barrier to users.

The test is proof that in most cases, users prefer to solve tasks using the chart, even if it is not accessible, instead of using the data table. This confirms the results of other studies in which the use of the residual vision was preferred over other strategies [65, 66].

The tooltips, which, as we have highlighted previously, have been highly valued by all users, have been shown to be useful for: (a) giving direct access to the data associated with each mark, avoiding forcing users to consult the data table; and (b) serving as an alternative or complement to the legend. However, tooltips generated by Highcharts library do not comply with the accessibility recommendations of WCAG 2.1 and part of the literature [95, 96], as it is not possible to hide them in case of overlay with other elements.

The order of the bars was key to interpret the time series data for users 3, 4 and 6. The recommendation of sorting the axes chronologically is also cited in the literature [97, 98].

Users 1, 2, 4, 5, 7, 10, 11 and 12 solved the tasks using the browser zoom set between 110 and 200%. In the accessible version of the charts, this means that content needs to reflow to avoid horizontal scrolling, clipping, or overlapping of elements. This functionality associated with the responsive web design technique is implemented by the Highcharts library, but in some cases, it has presented some unexpected behavior that has involved usability problems that of course affects accessibility, such as some labels disappearing (see Fig. 5).

Currently, Microsoft Excel does not provide accessible defaults for creating a new chart. However, it is possible to create fairly accessible charts. Exporting charts to non-Microsoft formats like HTML is also very problematic in terms of accessibility properties. Only an expert author will be able to create a moderately accessible chart.

The tasks were primarily centered on visual perception rather than testing data literacy and chart comprehension. Consequently, we designed the charts to be sufficiently clear and comprehensible for all users, regardless of their educational level. Notably, we found no significant differences in the results between users with the lowest educational attainment and the rest of the users.

At the outset of this publication, we conducted a theoretical comparison between the heuristic indicators proposed by Elavsky et al. [80] and our own set of heuristics. Although Elavsky and colleagues' work is highly relevant, our user tests were conducted prior to its publication, preventing a direct comparison. However, the theoretical analysis revealed that Alcaraz et al.'s set of heuristic indicators encompasses all the principles proposed by Elavsky et al. [80]. Notably, Elavsky's list comprises a larger number of more specific heuristics and aims to address a broader range of disabilities, whereas Alcaraz's heuristics are tailored to the specific needs of users with low vision.

The list of heuristic principles associated with this research also includes certain principles that provide advantages or help in overcoming accessibility challenges for individuals with various disabilities, including those who are blind, have motor or cognitive impairments. These principles, considered as a universal set of best practices, offer benefits to the wider public, irrespective of their disability status. Table 11 provides a summary of these principles.

The results of the user tests underscored the importance of incorporating tooltips or directly labeling data on the chart's marks as an alternative or complement to using legends (H2). Tooltips and direct data labeling provide users with immediate access to data associated with each mark, eliminating the need to consult the data table or scroll through the interface. Additionally, they reduce cognitive load and promote more efficient information processing [94]. Data labels can also draw attention to specific data points, making them valuable when data values are essential [98]. However, when implementing tooltips, the following considerations should be taken into account: (a) tooltips should be hidden by default; (b) their use should be restricted to situations where concise and useful information is provided; (c) consistency in their usage across all charts is crucial; (d) ensure compatibility with both mouse and keyboard interactions; (e) use arrows, akin to comic bubbles, to guide users to the relevant element; (f) maintain sufficient contrast for readability; (g) avoid obstructing or concealing other related elements with the tooltip [99].

Furthermore, based on the test results, we will introduce two new requirements to enhance the H2 heuristic concerning legends: (a) The legend must be of sufficient size to enable users to distinguish the colors or patterns associated

Table 11 Summary of the advantages linked to adhering to the suggested heuristic indicators for different user profiles

User profile	Barriers/rationale	Heuristic related
Blind	Inability to access visual content	H1. Title H2. Legend H3. Axes titles H4. Caption H5. Abbreviations H6. Data source H8. Short text alternative H9. Long description H17. Device independent navigation
Motor	Difficulty in using the mouse or keyboard Ensuring accessibility for this group relies on making interactive elements, like buttons and selectors, large enough and ensuring tasks are designed with ample completion time and minimal required actions	H14. Resize H17. Device independent navigation H18. Customization
Cognitive	Challenges arising from language comprehension and content complexity Users who rely on screen readers benefit from heuristic principles designed for individuals with visual impairments, including concise alternative texts and comprehensive descriptions, which also serve as condensed representations of complex material	H1. Title H2. Legend H3. Axes titles H4. Caption H5. Abbreviations H6. Data source H8. Short text alternative H9. Long description H18. Customization
Any user	Challenges in comprehending the message conveyed by a statistical chart Heuristics principles play a valuable role in enhancing the readability of charts for all users, not just those with disabilities. Principles related to content customization (e.g. H14 or H18), allow users to tailor the presentation to their preferences or device characteristics, improving overall user satisfaction during content interaction	H1. Title H2. Legend H3. Axes titles H4. Caption H5. Abbreviations H6. Data source H7. Print version H12. Legibility H13. Image quality H14. Resize H15. Without disturbing elements H18. Customization

with each mark effectively; (b) The legend must be positioned either at the bottom of the chart or in a standardized and highly visible location.

6 Conclusions and future work

The user test aimed at validating heuristic indicators for assessing the accessibility of statistical charts has provided valuable insights. The study involved 12 users with different low vision conditions, and the accessible versions of charts demonstrated superior efficiency, effectiveness, and user satisfaction. The evaluation conducted using the think-aloud method allowed us to visualize, from the users' perspective, those elements that constitute barriers to task completion, as well as the strategies that each user employs to overcome them. Another crucial aspect of these user tests has been the opportunity to comprehend specific preferences that may not necessarily align with the best practices commonly acknowledged in the existing literature. A notable example is the preference for color charts, even among users with CVD.

From a qualitative point of view, the heuristics related to legends (H2), axes (H3), data source as a data table (H6), safe colors (H10), contrast (H11), legibility (H12), image quality (H13), resize options (H14), focus visibility (H16), avoid disturbing elements (H15), and independent navigation (H17) proved to be crucial for task performance.

Legend (H2) is essential to understand the data. Its position and size, as well as the colors (H10) and contrast (H11) used, can negatively influence the effectiveness and efficiency if they are not designed following accessibility guidelines. On the other hand, labelling the values directly in the chart marks or implementing tooltips are even better alternatives. For users with CVD, it is essential to use safe color combinations or patterns to differentiate the marks. However, the combinations based on white, black and grey produce an effect of visual saturation in certain users, especially in those who preserve the perception of color. Considering the suitability of color to encode categories [100] and that some users prefer it over monochrome interfaces, a possible conclusion of the test is the need to redundantly encode categories with colors and patterns as well, to target all profiles.

Of equal importance to the legend are the titles of the axes (H3). Both have been used by all users to understand the data. Using vertical text on the y-axis does not seem to have been a problem for any user. On the contrary, low-quality images of text hinder the legibility of the legend and axes text (H13).

Providing access to the data source as a table (H6) allows users to have a highly efficient, fully text-based alternative when the task involves searching for a particular datum. Also, as observed during the test, it is useful to verify an answer before delivering the task. For this reason, and considering the challenges faced by individuals with more severe low vision in accessing charts, the presence of an equivalent table becomes indispensable.

Another common barrier has been insufficient image quality (H13) of non-accessible charts to cope with demanding resizes (up to 500%) (H14). In such cases, legibility (H12) is compromised and the use of charts in vector format is the best alternative because they can be enlarged as much as necessary without losing quality [37]. Another of vector charts' advantages is their complete integration with the Document Object Model (DOM), that grants the ability to manipulate and customize them as any other HTML element and makes them compatible with assistive technology [101, 102].

Other works highlight the difficulties that users with low vision experience when interacting with screen magnifiers [103–105], because they only have a partial view of the page they are interacting with, and this can cause loss of context since not all the elements necessary to interpret or interact with the content are displayed on the screen. This is a common issue when interacting with a chart whenever the task requires comparing data. This requirement seems to lead to designs with reflow, to avoid horizontal scrolling, clipping, or overlapping of elements (H14), but this only worked for users using browser zoom and not for those using screen magnifiers with magnifications much greater than 200%.

The heterogeneity of needs and preferences among participants leads to test personalization techniques (H18) as a key factor to ensure the best accessibility in the greatest number of possible situations. However, as other works point out [63] one single method of adapting the presentation of the charts may not be sufficient to meet all the requirements for people with low vision.

With the user test conducted in this research, we have successfully followed all the steps outlined in the methodology by Quiñones et al. [81], affirming the validation and reliability of our heuristic set.

In these tests, the authors decided to start with simple charts. With more complex charts it might be possible to find a larger number of barriers (this was even mentioned by users 2 and 8).

As a future research direction the authors aim to test how complexity affects the barriers encountered by the users and also the effect of customization options (H18), to allow users to change mark colors, font style and font size, among others.

The main line of future work is trying to recruit new users, to cover most low vision profiles to continue reviewing the list of heuristic indicators and improve it by refining the guidelines and doing a new iteration in the definition and scoring of the heuristic set. Further work is required to plan other types of tasks that allow validating some of the heuristics not contemplated in this study (H1, Title; H4, Caption; H5, Abbreviations; H7, Print version; H8, Short text alternative; H9, Long description; H18, Personalization).

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Author contributions R.A. and M.R. have overseen the conceptualization, administrated of the research, and the bibliographic search. R.A. and M.R have defined the methodology. A.A and A.P have conducted and record the user tests. R.A and M.R. wrote the main manuscript text and prepared all the figures. All authors have performed an initial review of the manuscript. Finally, M.R has conducted a formal review of the entire manuscript.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethics approval The research follows the ethical code of AIPO (ACM Spanish local chapter) https://aipo.es/wp-content/uploads/2021/02/codigo_etico_AIPO.pdf.

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