Methodology for heuristic evaluation of the accessibility of statistical charts for people with low vision and color vision deficiency

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Abstract
Statistical charts have an important role in conveying, clarifying and simplifying information and have a significant presence in fields such as education, scientific research or journalism. Despite numerous advances in the field of digital accessibility, charts are still a challenge for people with low vision and color vision deficiency (CVD) and create barriers that hinder their accessibility. The research presented in this paper aims is to create a heuristic set of indicators to evaluate the accessibility of statistical charts focusing on the needs of people with low vision and CVD. The set of heuristics presented has been developed based on the methodology by Quiñones et al. (Comput Stand Interfaces 59:109–129, 2018, https://doi.org/10.1016/j.csi.2018.03.002), which consists of 8 stages: (1) a state of the art literature review; (2 and 3) analysis and description of the most relevant information obtained from this research; (4, 5, and 6) selection and specification of a first set of heuristics relating them to existing heuristics; (7) validation; and (8) refining the set to obtain a final list of heuristics. A first set of heuristics (17 indicators) has been developed and applied on two heuristic evaluations, and has been amplified to 18 indicators. The final set covers the needs of the user profiles with low vision as well as the needs of the CVD and poor contrast sensitivity users. This research is a first step to widen accessibility requirements to statistical charts and to take into consideration users with low vision and CVD, often forgotten in accessibility research.

Keywords Accessibility · Charts · Graphs · Information visualization · Low vision · Color blindness · Heuristic evaluation

1 Introduction
Statistical charts improve the understanding of big volumes of data very efficiently and reduce the cognitive load associated with reading and digesting textual and tabular information [1]. Therefore, charts have an important role in conveying, clarifying and simplifying information, thus making information more accessible to everybody [2]. Charts have a significant presence in fields such as education, scientific research, journalism, marketing or business intelligence, which justifies the need to ensure access to this type of information to people with disabilities. Moreover, the open data movement and the open distribution of big datasets to citizens particularly by governments on their stride for transparency have had a big impact on the self-named “data journalism” increasing the number of charts and graphical presentations included in media with a surge of interest among journalists, academics, computer scientists and designers [3] on this type of content. On the business side, this democratization of data has led to the demand for new professional profiles trained in the analysis, management and visualization of data, to the point that in countries such as the USA, it is expected that by 2020 jobs related to data science will increase from 364,000 to 2,720,000 [4].

Although the last decade has seen many advances in the accessibility field, accessible visualizations for visually impaired users are still scarce. Hence, statistical charts currently present important barriers that hinder accessibility for visually impaired users.
Low vision is defined as the condition under which a person’s vision could not be corrected completely with correcting lenses. Low vision means that, after the best optical lenses correction, a person has less than 0.3 visual acuity, or a visual field of less than 20°. Low vision difficulties may be classified under 5 different categories: visual acuity, relating to clarity of vision; light sensitivity, which can impede or hinder reading bright screens; contrast sensitivity, which affects distinguishing two colors with low luminance distance; field of vision, which may mean losing central vision, losing peripheral vision or a random field vision caused by occlusions or black spots; and color vision deficiency (CVD), most popularly known as color blindness, caused by the loss or degeneration of retinal cones, the perception organs responsible to detect the different color wavelengths affecting red (the most common, protanopia), green (deuteranopia) or blue (the most uncommon, tritanopia) or all of them [5]. Under this big umbrella we distinguish three severity levels: (B1) From no light perception in either eye up to scarce light perception, and an inability to recognize the shape of a hand at any distance or in any direction; (B2) From ability to recognize the shape of a hand up to visual acuity of 20/600 and/or a visual field of less than 5°; (B3) From visual acuity above 20/600 and up to visual acuity of 20/200 and/or a visual field of less than 20° and more than 5°. Finally, one can include also in this group people with different degrees of color blindness or with difficulties to detect contrast. This diversity of profiles implies that each user’s group will use different assistive technology ranging from screen readers and screen magnifiers to simple customizations, and each of them will also use different strategies—keyboard, mouse, zooming—to navigate through information, in order to profit from the residual vision they have or they will use alternative means such as voice. Screen reader users or magnifier users cannot be strictly differentiated as many people with low vision will combine different techniques and tools depending on the context, needs and preferences.

Moreover, this intrinsic complexity of low vision profiles is amplified with situational visual disabilities, where context conditions may affect every person, with or without low vision. A typical example of a disabling context is the level of ambient light [6], that can drastically reduce readability and, therefore, create situations very similar to intrinsic loss of vision. Another is excessively bright solar light, which may affect contrast perception on a screen and may reduce color differentiation [7], with perceptions very similar to those of CVD users. It is common for these disabling contexts to appear during the interaction with mobiles on real life scenarios; it is not too risky to assimilate mobile users with people with disabilities, and, in particular, with low vision users, as they share many similar barriers to access the information [8]. Therefore, solutions provided to low vision users can benefit a great number of users, taking into account the adoption of smartphones in our society, and the acquired sovereignty of mobiles as the main channel to access Internet [9].

A previous literature research by the same authors [10] unveiled an important lack of publications and guidelines focused on the accessibility of statistical charts for people with low vision and CVD. This identified gap adds to the existing marginality of a user group representing the 97% of people with visual disabilities [11] in the field of accessibility research. In order to address it and in the context of a bigger project to improve the accessibility of statistical charts for people with low vision and CVD, in this article the authors introduce a tool to evaluate the accessibility of statistical charts within a web-based environment with particular focus on the needs and barriers related to low vision and CVD.

2 Related research

The Web Content Accessibility Guidelines [12] are the reference document for digital accessibility, they have even been acknowledged as an ISO standard [13], and they have been adopted by many countries as the minimal legal requirement for public (and in some cases even private) websites to comply. In the case of Europe, the WCAG 2.1 has been integrated into the ISO Standard 301 549: Accessibility requirements suitable for public procurement of ICT products and services in Europe v2.1.2 [14] a reference standard determining the accessibility of websites and mobile applications of public sector organizations. WCAG are organized under four theoretical principles covering every aspect of accessibility: perceivable, operable, understandable and robust. Every principle is detailed in several specific guidelines, which in turn are translated to directly evaluable criteria under three levels of conformance.

WCAG, by definition, covers all types of web digital resources and types of information, and while it includes graphical content—with an improvement on contrast issues in its last version, WCAG 2.1—it’s general character means that they cannot thoroughly explore every aspect of statistical charts. Based on them, Boudreau [15] has recently created a list of general heuristics and Koivunen and McCathie-Nevile [16] created heuristics related to graphical content. For his part, Brajnik [17] collects a list of the main accessibility barriers for people with low vision and relates them to the success criteria of the WCAG 1.0 and 2.0, as well as to the Italian legislation.

On the other hand, independently of WCAG but also concerning accessibility, and addressed to content authors, there have been several initiatives to publish recommendations,
guides or guidelines related to the authoring of accessible statistical charts. One relevant project is the National Center for Accessible Media (NCAM) guidelines [18], further developed by the Image description guidelines by the DIAGRAM Center [19], which recommends some best practices for bar charts, line charts, pie charts and scatter plots, among others. These guidelines focus accessibility efforts on textual alternatives: accessible and equivalent tables or lists for complex charts, summaries of the content detailing the type of chart and main patterns for simpler charts, as well as promoting the use of clear titles, axes labels and legends.

With a more business-oriented vision and a more general scope, but also for authors, Evergreen and Emery [20] have created a data visualization checklist, relying on design principles collected by the same authors [21], which covers aspects such as text, arrangement, color and lines of charts. This checklist has been rigorously tested by Sanjines [22].

Regarding the use of textual alternatives, though not oriented specifically to charts, but to a broader set of image types, the work of Splendiani [23] focuses on how to textually describe non-text content for scientific articles. Previously, the analysis of computer science journals conducted by Splendiani and Ribera [24] had already shown a deficit in the use of text alternatives, safe color combinations on the marks of the charts, an insufficient font size, or the use of images with a minimum resolution and dimensions. Simon et al. [25] show that the most common problem with charts and figures in the proceedings published by the Innovation and Technology in Computer Science Education (ITiCSE) are captions that do not adequately describe the figure and the use of font sizes too small to be readable.

3 Method

The research presented in this paper is based on the Heuristic Evaluation (HE) method, one of the most efficient usability evaluation techniques without users. Streamlined, the HE is a usability engineering method for finding the usability problems in a user interface design so that they can be attended to as part of an iterative design process. It involves having a small set of evaluators examine the interface and judge its compliance with recognized usability principles (the “heuristics”) [26]. Two important aspects must be taken into account when using HE: first, the building of the list of principles and, second, the definition of severity ratings associated to each principle.

The HE general method has been adapted to the creation of a list of heuristic indicators to evaluate the accessibility of statistical charts considering the needs of low vision and CVI users, with the aim to be very clear and easy to apply. Although there is no a clear agreement on the best suitable process or methodology to develop heuristics [27] within the literature, there are many proposals of sets of heuristic indicators to evaluate usability, user experience or accessibility in several specific fields, similar to the objectives of this article. These studies commonly do not explain the procedures to formulate, specify, validate or refine the list of heuristic indicators and in general are an extension or an adaptation from renowned and well adopted lists such as the ones created by Nielsen [28], Weiss [29], Perlman [30] or, relating accessibility, directly from WCAG. The initial lists do not dive into particular interface features nor in very specific products or applications, dealing instead with very general features, and they need an extension to cover other specific requirements. In the literature there exist also other publications dealing with the methodology of developing a list of heuristic indicators [31–38].

This research adopts the proposal by Quiñones et al. [38] of a formal and systematic methodology as the framework of reference and complements it with the metrics proposed by Jiménez et al. [37] to validate the efficiency of the proposed indicators compared to an existing heuristic list control. This methodology consists of eight stages:

1. Exploratory stage: in this stage the researchers must do a literature review with the goal to collect relevant information in order to develop the heuristic indicators list;
2. Experimental stage: in this stage the researchers analyze data obtained from several previous experiments to retrieve additional information not identified during the first stage;
3. Descriptive stage: researchers select and prioritize the most important questions within the collected information during stage 1 and 2;
4. Correlational stage: researchers try to reconcile domain features and functionalities with user experience principles and attributes related to them, as well as with existing heuristic indicators. If there is no existing heuristic, researchers only match the feature with the usability/UX attribute;
5. Selection stage: the researchers review the list of indicators created since then and decide whether to keep, adapt or delete them;
6. Specification stage: in this stage researchers specify in a formal way each indicator. In this stage it is recommended to create a template with the following information per indicator: identifier, priority, name, definition, explanation, function or feature evaluated, examples, benefits, problems that may appear to understand or apply the criterium associated to the indicator, UX or

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1 The checklist is also available at http://stephanieevergreen.com/wp-content/uploads/2018/02/DataVizChecklist_Feb2018.pdf.
usability attribute evaluated by the indicator, source where the indicator was taken from;
7. Validation stage: in this stage researchers validate the set of heuristic indicators taking into account their efficiency, through different experiments, experts’ judgement or user tests;
8. Refining stage: in this stage researchers refine and verify the set of indicators with the conclusions or comments resulting from stage 7.

The list of heuristics obtained through this procedure could potentially be applicable to statistical charts in different formats or media such as printed documents, digital office documents, apps, etc. In this research, in order to avoid a not particular enough tool, the authors decided to focus the evaluation on charts published in the web, postponing the study of other media or formats to future work.

As mentioned above, the list of heuristics proposed in this work is intimately associated with WCAG, which are its starting point and inspiration. In this direction, for a chart to be accessible it is a previous requirement that the website containing it is accessible as well, i.e., the web has to comply with the success criteria established by WCAG. On the other hand, WCAG criteria covers some requirements affecting assistive technology used by low vision and CVD users, for example requiring to explicitly code the language of the page for screen readers; these requirements are not exclusive to statistical charts, but they are needed for those users accessing the chart content through a screen reader.

For practical reasons the authors have decided not to include them in the list of heuristics, which has to be understood as complementary to WCAG.

3.1 Exploratory stage

As a first step, in order to obtain a very comprehensive list of indicators the authors carried out a thorough review of WCAG 2.1 and concomitant documents and tried to gather all criteria related to the subject of this work. This review focused its attention to success criteria of level A and AA, required by law in many countries, and ignored any criteria not related to charts or charts’ interaction. The authors compiled a table including each relevant criteria together with a list of sufficient and advisory techniques associated to them, since they delimit and better define each success criteria, and a description of the implications of failure. The impact description was based on the information gathered from the document Understanding WCAG 2.1 [39] and from other cited works, and mainly from authors’ previous experience working with low vision users in other projects (see Table 1).

As a second step the authors carried out a literature scope review about statistical charts accessibility for low vision and CVD users [10], in which they confirmed that previous research covered quite notably accessibility of charts for blind users but paid very low attention to the needs of users with low vision or CVD.

Solutions provided in the literature to promote the accessibility of charts include the creation of textual alternatives, haptic alternatives and sonification as strategies to convey chart information and even the combination of two or more of these strategies to offer multimodal access to the content. Relating textual alternatives, a wealth of research deals with methods to automate the creation of summaries or long descriptions of charts. Relating sonification, research has studied how sounds and vibration can convey, particularly to blind users, trends and quantitative or qualitative information. Finally, tactile alternatives are used from long ago, and rely on Braille and different kinds of embossing paper to generate accessible versions of charts, mainly for blind users.

Although the proposed alternatives for blind people could also benefit people with low vision and CVD, this user group keeps some visual faculties and wants to use them on their daily activities [41], which is not exploited in the above mentioned solutions. Taking into account this lack of studies for low vision needs, the initial literature research scope was redefined to include accessibility solutions for low vision, not necessarily related to statistical charts. A summary of the relevant information obtained during the exploratory stage is described in the following sections. It is organized within three categories: information, presentation and behavior.

3.1.1 Information

Within this category there are all the elements which help explain the chart content. Statistical charts include several characteristic components that confer them precision, order, clarity and communication ability [42]: these elements include the title, the axes, legends, symbols and labels. For the sake of comprehensiveness captions can also be included in this category as they include rich and explanatory content about the chart [43, 44]. This is due to that they often contain the most important research results [45] or relevant data necessary for the understanding of that content. All these elements have an important role to help understanding the message and data communicated by the chart.

Quantitative axes show the range of numerical values of the displayed variable. Categorical axes show different values of the dataset, often resulting from some aggregation (countries, products lines, users’ groups, etc.). Feria [42] recommends to never hide the axes or labels for aesthetic reasons. Often the axes extend into a chart grid that helps the user to visually identify the value of each mark. Feria recommends regulating the density of the grid looking for an equilibrium between clutter and informativeness. Labels of
| Success criteria | Sufficient and advisory techniques\(^a\) | Implications of failure for users with low vision | Implications of failure for users with CVD |
|------------------|----------------------------------------|-----------------------------------------------|------------------------------------------|
| 1.1.1 Non-text Content (A) \(^b\) | G95: Providing short text alternatives that provide a brief description of the non-text content  
G73: Providing a long description in another location with a link to it that is immediately adjacent to the non-text content  
G74: Providing a long description in text near the non-text content, with a reference to the location of the long description in the short description  
G92: Providing long description for non-text content that serves the same purpose and presents the same information | When a textual alternative is not provided, users with low vision that rely on a screen reader as a complement to other assistive technologies will not be able to access the information contained in the chart \([10, 16, 17, 23]\) | When the chart uses not safe colors \(^c\) and no textual alternative is provided for the color scheme, users with CVD will have difficulties to perceive the properties of data encoded through \([7]\) |
| 1.3.3 Sensory Characteristics (A) | G96: Providing textual identification of items that otherwise rely only on sensory information to be understood | Users that rely on screen magnification to view the chart have a harder time navigating through their elements than users viewing the chart in its original size. If design relies only on sensory features and these are difficult to distinguish, this could result in important barriers to the use of the chart. Additionally, if shapes are not big enough, they could be difficult to differentiate \([5]\) | – |
| 1.4.1 Use of Color (A) | G14: Ensuring that information conveyed by color differences is also available in text  
G11: Using color and pattern | – | – |
| 1.4.3 Contrast (Minimum) (AA) | In all cases  
G174: Providing a control with a sufficient contrast ratio that allows users to switch to a presentation that uses sufficient contrast text is less than 18 point if not bold and less than 14 point if bold  
G18: Ensuring that a contrast ratio of at least 4.5:1 exists between text (and images of text) and background behind the text text is at least 18 point if not bold and at least 14 point if bold  
G145: Ensuring that a contrast ratio of at least 3:1 exists between text (and images of text) and background behind the text | Low contrast graphical information or text is less accessible for low vision users, and in particular to the users with low contrast sensitivity \([5, 16, 17]\) | If information is conveyed exclusively through color, users with CVD could lose details of important features of the chart \([5, 10, 17, 23]\) |

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\(^a\) These are examples of sufficient and advisory techniques.  
\(^b\) WCAG 2.1 success criteria for accessibility.  
\(^c\) Not safe colors are those that do not meet the contrast requirements for accessibility.
| Success criteria | Sufficient and advisory techniquesa | Implications of failure for users with low vision | Implications of failure for users with CVD |
|------------------|-------------------------------------|-----------------------------------------------|------------------------------------------|
| 1.4.4 Resize text (AA) | G142: Using a technology that has commonly-available user agents that support zoom G146: Using liquid layout G178: Providing controls on the Web page that allow users to incrementally change the size of all text on the page up to 200 percent G179: Ensuring that there is no loss of content or functionality when the text resizes, and text containers do not change their width | If font size is too small and it cannot be amplified, legibility is not ensured [5, 16, 17] If font size is coded with absolute units or the layout is not responsive, magnifiers reducing the visual area could result in overlapping content, horizontal scrolls or elements disappearing from the users' view [5, 16] | – |
| Others techniques | Providing large fonts by default Avoiding justified text Providing sufficient inter-line and inter-column spacing Avoiding the use of text in raster images Ensuring that text in raster images is at least 18 pt | – | – |
| 1.4.5 Images of Text (AA) | G140: Separating information and structure from presentation to enable different presentations | Text images do not allow customization of font family, font size, color, etc., hindering its perception for low vision users [5, 16] Additionally, bitmap images of text lose resolution when magnified [2] | Some users with CVD use a personal CSS on the browser to personalize colors. This will have no effect on image text [2] |
| 1.4.11 Non-text Contrast (AA) | Graphics with sufficient contrast G209: Provide sufficient contrast at the boundaries between adjoining colors G18: Ensuring that a contrast ratio of at least 4.5:1 exists between text (and images of text) and background behind the text G145: Ensuring that a contrast ratio of at least 3:1 exists between text (and images of text) and background behind the text G174: Providing a control with a sufficient contrast ratio that allows users to switch to a presentation that uses sufficient contrast | When foreground and background contrast in both text and graphical elements is not enough many users could not be able to distinguish figure elements or to read content [5, 16] | When color is used to encode variables and the different values do not offer sufficient contrast users with CVD may not be able to distinguish them [5, 16] |
| 1.4.12 Text Spacing (AA) | Line height (line spacing) to at least 1.5 times the font size; Spacing following paragraphs to at least 2 times the font size; Letter spacing (tracking) to at least 0.12 times the font size; Word spacing to at least 0.16 times the font size | Low line spacing could hinder legibility [5] | – |
| 2.1.1 Keyboard (A) | G202: Ensuring keyboard control for all functionality | Screen reader users rely on keyboard to navigate the content, so when elements only react to mouse interactions, they become useless [40] | – |
| Success criteria | Sufficient and advisory techniques<sup>a</sup> | Implications of failure for users with low vision | Implications of failure for users with CVD |
|------------------|---------------------------------------------|-------------------------------------------------|-----------------------------------------|
| 2.1.2 No Keyboard Trap (A) | G21: Ensuring that users are not trapped in content | Screen reader users may only be able to navigate by keyboard, and a keyboard trap will be a dead end for them [40] | – |
| 2.4.3 Focus Order (A) | G59: Placing the interactive elements in an order that follows sequences and relationships within the content | If users rely on text to speech output to access graphical elements, a wrong order can be very confusing [40] | – |
| 2.4.6 Headings and Labels (AA) | G130: Providing descriptive headings G131: Providing descriptive labels | Not providing textual elements such as title, legends, captions or labels can hinder chart comprehension for low vision, CVD and any other user [10] | – |
| 2.4.7 Focus Visible (AA) | G149: Using user interface components that are highlighted by the user agent when they receive focus G195: Using an author-supplied, highly visible focus indicator | Users can be lost without an indication of their current point of focus, and usually zoom interaction implies constant zooming in and out with important changes of context [5] | – |
| 2.5.1. Pointer Gestures (A) | GXXX: Do not rely on path-based gestures GXXX: Do not rely on multipoint gestures GXXX: Provide controls that do not require complex gestures and perform the same function as complex gestures GXXX: Single-point activation for spatial positioning and manipulation | Following a path or multipoint interaction can be complicated on a zoomed screen [8] | – |

<sup>a</sup> After each criterion, its conformance level is indicated (A o AA)  
<sup>b</sup> At the end of every technique or recommendation the W3C identifier is included  
<sup>c</sup> Not safe colors: this term refers to color schemas that are not clearly distinguishable for users with deuteranopia, protanopia or tritanopia
the axes, if correctly and clearly written, purvey the meaning of the chart by themselves beyond title or caption. For excellent comprehension it is recommended to include their units and precision level (e.g., thousands of gallons, millions of years) on the title of the axes.

Legends are key to unequivocally interpret the encoding, making transparent the relation between numerical values with a color scheme, for example. Legends can be offered as an external, general key to all possible values, or inside the chart, close to each mark. Evergreen and Metzner [21] recommend to label data directly, close to marks (on top of or next to bars and next to lines), as they reduce cognitive load and foster a more efficient information processing. For Knaflic [46] data labels themselves can help to draw attention to certain data points, so they are useful if the data values are important. In this case it is possible to eliminate axes and instead label the data points directly to avoid the inclusion of redundant information. However, if users have to focus on big-picture trends, Knaflic recommends preserving the axes, to decide between both options authors may consider the required level of specificity. Additionally, comments, annotations or explanations enrich the chart with textual information providing context information.

Finally, image captions contribute a brief comment or explanation to the accompanying chart. Although many times they simply complement the title, their objective is not to repeat it but to contribute to a better understanding of the chart [47], including its purpose [48] when they include additional information. Several authors emphasize the importance of captions to understand a graphic [44, 49, 50], as it offers a synthesis of the most important aspects displayed in the chart, and its principal conclusions [45]. Splendiani [23] collected some recommended information to include in captions derived from style guides and scientific editorials, which for statistical charts consist of: identifying and explaining labels, abbreviations, data sources, usage rights and units and describing details of statistical analysis (standard deviation, p value, etc.).

The need to include alternative text and long descriptions has already been described in the section analyzing WCAG. In the case of charts, alternative texts cannot be used to describe the content (it requires longer explanations) and it just serves to briefly inform about the contents of the chart and to help users decide if they want more information about it [51].

In the literature, the most common approach to provide an accessible solution to a chart is to provide an alternative as a data table, especially when dealing with blind users [19]. As a drawback, tables do not show so efficiently trends, variable comparisons, and therefore require more short-term memory workload and a bigger cognitive load when trying to reach conclusions or insights from the data. In fact, one of the main benefits of displaying information through a chart is to make invisible information visible [52]. As an advantage, tables are sometimes a required complement; for example, to bitmap images where values are not readable by screen readers, in order to be able to lookup a specific value; W3C [51] includes data tables in its proposal for long description of statistical charts.

Long descriptions, on the other hand, enhance the chart understanding for users with low vision and other users’ profiles that may not be able to understand the graphical content. Long descriptions could be offered on an external web page, within the alt attribute or just after the chart as part of the web page content [53], this last option being the one preferred by users [54]. Ault et al. [55] argue that a well written long description could serve, by itself, as an actual alternative rich enough to ensure a good level of accessibility for statistical charts. Corio and Lapalme [56, 57] consider them a rich complement to understand the message communicated by the chart. In any case, as repeatedly argued in the article, visualization has some advantages never attainable with textual alternatives.

3.1.2 Presentation

This level includes all aspects related to the visual display of the chart: layout, text composition, typography, color use, among others.

Legibility is an important feature of content. According to Legge [58], a good legibility means that users can perceive text and to distinguish a character from another without ambiguities. The more distinguishable, the more legible. Previous research targeted to low vision users and elderly people, provides hints on how to display text to accommodate the needs of these users. Some of the mentioned features, directly affecting legibility, are font family, font size, contrast [59], text align and spacing. On the web context there are many mechanisms to personalize or customize these features.

In the literature there is no consensus on which font family is better for low vision users, although there is general agreement to recommend sans serif typographies such as Arial, Helvetica, Courier or Verdana, rather than serif font families such as Times New Roman [60]. All recommendations agree on not recommending decorative or fantasy font families. Organisms related to vision have even created specific fonts for low vision users, the American Printing House for the Blind (APH), developed APHont.2

The Scientific Research Unit of the Royal National Institute of Blind People developed the Tiresias font. To the authors’ knowledge there is only one study comparing the performance of Tiresias to more common font families, and

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2 https://www.aph.org/products/aphont/.
it does not demonstrate better results [61]. The Laboratory of Cognitive Technologie, in Marseille, France, developed Eido, focused on making letters simple and different as well, while being still recognizable by common readers. Bernard et al. [62] present an experiment where Eido is useful for people with central field of vision loss (such as macular degenerative) but with no effects in reading speed compared to Courier font family.

Also related to the font family and taking into account that statistical charts often display a big proportion of numbers in labels, legends or even titles, it is very important that numbers are very distinguishable between them and with letters. A typical example of confusing representations is the characters 1, l letter and lowercase i. This requirement may be more important than other considerations.

Left align and flush left promote a regular reading pace and a better legibility [63], while justified text may cause bigger difficulties, due to the white space “rivers” generated by irregular spacing [5]. This does not apply to number alignment in tables, where it is important for the same units to be aligned. Kerning, word spacing and line spacing [64, 65] are also relevant, in particular to users with central field loss [66]. Regular letters are the most legible, and therefore it is not recommendable to include a great proportion of italics or capital letters [5]. Low vision users benefit from big font sizes, above 14 dots and preferably between 16 and 18 dots [60], and with the possibility to increase them through the browser options or through their assistive technology. Offering personalization is a good practice because it is the easiest way to satisfy the specific needs of every user, that cannot be identical to the established good practices [67]. For example, people with peripheral vision field loss but with a good vision acuity prefer using smaller font size, in order to read more text on their constrained field of view [5].

Column width may affect legibility for users with low vision. In particular, too long lines require an additional effort to users with reduced vision fields, as they have to make more horizontal and vertical movements [5]. In this direction, when a word is cut at the end of the line, it is better not to use syllabification as it derives on a higher difficulty to read and understand the text [5].

Elements layout must follow Gestalt principles. Related elements must be grouped, for example the title should be close to the chart it describes [5], and non-related elements must be separated by spaces and margins.

When the different textual elements (title, legends, captions, axes, labels, etc.) on screen are differentiated only by size and the user applies zooming, the originally bigger ones may appear too big and do not fit on screen. It is therefore recommended to combine several attributes to differentiate elements such as color, underlining or font family [5].

When the chart is provided as a bitmap authors must pay special attention to the file format. A file format is a standardized way to codify the digital information which defines the structure and the type of data stored on a file. Among the most popular file formats for graphics in the web it is worth mentioning JFIF (JPEG File Interchange Format), a lossy format standardized by the Joint Photographs Committee, and PNG (Portable Network Graphics), a lossless format, open standard, created by the W3C to substitute GIF, subject to some proprietary restrictions. JFIF is well known for its ability to display photographic images with a high level of compression, obtaining high quality pictures with very small size files; on its side, PNG has a better compression performance when used on images with big areas of uniform color (charts, icons, flags, etc.) with even higher compression rates than JPEG. PNG is also better when dealing with images combining both text and flat colors. JPEG is a lossy format, which means that, in order to reach a high compression, it loses some details of the original image that will be unrecoverable; this may result into a lower quality or may cause some “image artifacts” on big uniform areas. Consequently, if the original chart mainly uses flat colors and there is not a high demand of compression the recommended format is always PNG. Both formats accept different levels of compression to adjust quality, with less compression fostering fidelity and high compressing reducing file size. In summary, it is preferable to use lossless formats or if needed, use lossy formats but with a low level of compression which does not affect the output quality.

In bitmap images, quality is the result of file format, type and level of compression, as we have seen, but also of pixel size, resolution and bit depth [23]. In the context of this article it is important for source images to have a size big enough to be zoomed ×2 without losing clarity, this is without pixelation or blurring. Resolution is the number of pixels divided by longitude, indicated in pixels per inch (ppi) or dots per inch (dpi). Different screens may show the same graphic at different sizes because screens have their own resolution as well. Independently of the screen, when an image has a bigger resolution it can display a bigger quantity of differentiable details. Some recommended thresholds are 150 dpi for screen and 300 dpi for printing, but this does not consider the zoom requirements. These resolution demands depend also on the complexity of the chart, and the density of elements displayed in it; very simple charts with one or two big elements will go with lower resolutions. Bit depth is defined as the number of bits per pixel used to codify the color. Color may be codified from a lookup table with 8 bits (only 256 different colors) or as true color codifying each color channel (RGB) with 8 bits (255 values) plus,
optionally, 8 more bits to codify transparency (alpha channel), resulting in a bit depth of 24 or 32 respectively.

For vector images, the format most widely used is SVG (Scalable Vector Graphics), a W3C recommendation based on XML. Vector images, as opposed to bitmaps, can be magnified as much as desired without losing quality, because they are not rendered by pixels but by instructions, independent of the size. SVG format offers far more accessibility options than bitmaps in many contexts [2]. To mention some of the benefits, it can be started by its standardization and integration on the web pages Document Object Model (DOM), which allows to manipulate and customize them as any other HTML element and makes them compatible with assistive technology including screen readers [68]; the separation between structure, content and presentation [69]; the possibility to use ARIA roles or attributes for every SVG element which may transmit very detailed information about attributes and values included in the chart in particular, W3C has developed some ARIA roles and attributes specific for statistical charts [70, 71]. On the visualization landscape, SVG is used by D3[^4] and its derivative libraries Vega[^5] and Vega-Lite[^6].

Color is an essential attribute of charts and plays a crucial role in statistical charts’ accessibility. Beyond safe color and contrast issues, required by WCAG, scientific literature has studied color effectiveness to communicate statistical attributes. According to Ware [72], color is effective to differentiate qualitative variables, ordinal or nominal ones, but much less effective to communicate quantitative values. According to Mackinlay [73] when dealing with ordinal categories humans distinguish colors preferably by saturation (intensity of color) and then by hue (red, green, etc.). On the contrary, when dealing with nominal categories, hue is predominant.

Olson and Brewer [74, 75] studied the use of colors in maps considering people with CVD needs. They researched several color schemes for sequential, divergent or categorical values and tested them under CVD conditions to offer some restricted color safe combinations. The term “color safe” refers to those colors that, combined, are distinguishable by people with CVD. To disseminate their work Brewer has created a free online tool, Color Brewer[^7] that let users choose a pertinent color schema under her own preferences (number of colors, type of values, color safe, etc.). Brewer schemes have been adopted by D3, Tableau and many other visualization tools.

Other authors, from the fields of optometry, HCI or information visualization, studied the utility of colors for specific tasks such as time series evaluation [76, 77], or big data statistical judgement [78].

It is worth mentioning that safe color schemes do not consider contrast requirements set in WCAG, more severe, and focused on color luminance (difference to the ambient white light). Many users, with age, lose retinal rods and are unable to clearly perceive colors with low contrast. This requirement is set by success criteria 1.4.3 and 1.4.11 within WCAG 2.1, relating foreground and background text contrast and adjacent graphical elements respectively.

### 3.1.3 Behavior

Specific interface features related to chart interaction are described in this section.

#### 3.1.3.1 Safe magnification

Although a chart provides typography with the correct font size, according to W3C guidelines and to abovementioned best practices, different vision acuity and field of vision coverage among low vision users may imply the need to further customize the zoom level or text size through web browser standard tools or through their own assistive tools. It is therefore paramount when using those additional resources for the content to still be viewable, and that elements do not overlap or shrink which would impede a correct view or reading [5].

Tooltips are short messages providing additional information on an element or a widget, fired when this element receives the cursor or mouse focus. Joyce [79], states some requirements for them to be accessible: (a) as by default tooltips are hidden, it is not advisable to include vital information in them; (b) restrict their use to situations where the given information is useful and concise; (c) use them consistently through all the charts; (d) make them compatible with mouse and keyboard as well; (e) use arrows, as in comic bubbles, to help users recognize which element does the tooltip refer to; (f) ensure a sufficient contrast; (g) avoid hiding or hindering other related elements with the tooltip—this last recommendation also contemplated by Van Achterberg [80].

#### 3.1.3.2 Printing

Reading on screen may introduce additional difficulties for some low vision users. It is common for these users to read from a very short distance from the screen which means a very harsh position causing fatigue [5]. Taking this into account, it is recommended to offer the possibility to print the content, and ideally personalized to the user to cover their particular needs [5].

Often the printed version is just black and white, and the chart readability is compromised, as sometimes color is the only means to transmit a particular data feature; this adds the need to use colors wisely and to offer sufficient contrast.

[^4]: https://d3js.org/.
[^5]: https://vega.github.io.
[^6]: https://vega.github.io/vega-lite/.
[^7]: Available at http://colorbrewer2.org.
3.1.3.3 Customization Overall, and taking into account the high variability of profiles, needs and requirements of low vision users, customization of the chart perceptual components (colors, typography, size, alignment, etc.) should be a desired offering on an accessible chart. Customization could be offered by the chart creator, through the selection of different style sheets controlling font family, color schemes and font size, among others, through assistive technology, or through specific API or software libraries, as for example, Infusion by the Inclusive Design Research Center in Canada, a plugin that any webmaster can add to their website which allows the readers to customize text size, font family, spacing or to apply high contrast colors. When customization is made through assistive technology, it is paramount that the code and scripts are standardized and tested for compatibility issues; when compliant, users would be able to access and manipulate content and styles from their own tool.

3.1.3.4 Real-time updates Some charts depict very time-dependent information, such as election results, sport results or stock numbers, and this information varies automatically along time. These changes must be communicated to the user, but the authors must try not to disturb or interrupt users too much or decide to delay communication until changes occurred affect a task in hand. In order to do so, the chart author must decide whether to interrupt the user or not, the level of data aggregation when communicating changes, etc.

3.1.3.5 Data export Parallel to printing, exporting the chart to different formats is important to tackle different needs and profiles of the target audience. Some of the suitable formats are the raw data as an Excel or Comma Separated Value file, or the chart in PNG, JPG or SVG. These options will allow the user to read the chart with their preferred tool, or even generate a haptic version with an embossed printer from the SVG file.

3.1.3.6 Voice interaction The possibility to interact with the chart by voice commands may benefit blind users, users with low vision and other profiles such as users with motor impairments. This implies that the chart is coded in actual text and all elements are correctly identified and described.

3.1.3.7 Sonification Finally, much of previous research deals with “sonification” techniques, defined as an information representation based on sound, not including voice [81]. Some works explored mapping charts to musical sounds [82], vibrations [83], using sounds to communicate trends [84] or using volume, pitch and position to represent quantitative and qualitative values [85]. Those options showed some good results for line charts or area charts, but they are not as useful for scatter plots [86]. Sonification is particularly suitable for blind users, while it does not fit very well users with low vision’s needs except when they have very limited sight.

3.2 Experimental stage

The objective of this stage was to analyze data obtained from several previous experiments to retrieve additional information not identified during the first stage (exploratory stage). However, the authors did not find any previous research with a focus on statistical charts accessibility for users with low vision or users with CVD, therefore, knowing that this was an optional stage, this stage was skipped and the efforts were focused on later stages.

3.3 Descriptive stage

In this stage the focus was on selecting and prioritizing the most important questions identified within the information collected during stage 1 (exploratory stage) and 2 (experimental stage). In this sense, all aspects relevant for the creation of the heuristic indicators were collected and selected. Table 2 shows the information collected.

3.4 Correlational stage

In the correlational stage, Quiñones et al.’s methodology [38] was used to map features and functionalities of the heuristic evaluation domain with attributes coming from the usability and user experience fields, as well as with additional pre-existing heuristic indicators, in an attempt to reconcile domain features and functionalities with user experience and attributes related to them.

Several authors have already proposed to match accessibility and usability guidelines [87–89] mainly trying to relate WCAG and Nielsen’s heuristics [28] concluding that there is a clear correlation between both. In this research, taking into account that the target domain is very restricted, the authors decided to try to match the indicators with Nielsen’s heuristics, with the heuristics and principles proposed by Koivunen and McCathieNevile [16], Evergreen & Emery [20] and Boudreau [15], Brajnik [17] and also with WCAG 2.1 success criteria, the third being more versed on graphical content while the last being the reference document for web accessibility. There is also a match between the different identified aspects with the different levels of vision and with pathologies related to low vision, in order to ensure a coverage of different needs through the indicators. Finally, the resulting heuristics are grouped into 5 categories: good...
practices, textual alternatives, color and contrast, legibility, and additional features and functionalities.

The resulting list (Table 3) includes many indicators, specific to statistical charts and their elements (axes, legends, data source, etc.) which do not find a counterpart in any other guideline; this result was expected due to the specificity of the domain of our list, and the broader scope of Nielsen’s heuristics, WCAGs or even Koivunen and McCathie-Neville [16] oriented to any type of chart.

### 3.5 Selection stage

In this stage, the objective was to review the list of indicators created up to this point and decide whether to keep, adapt or delete them. This procedure is summarized in Table 4: the “Action” column indicates how the indicator will proceed to the final selection, and whether it will be adapted to the specific domain, combined with similar or overlapping indicators, kept as an indicator per se or deleted as it is already covered by another indicator or it is not relevant enough. The column “Applicability” indicates how important that indicator is within the scope of this research, deriving importance from its capacity to solve accessibility problems related to statistical charts, and to cover needs of the different user profiles included in user with low vision and CVD.

| Topic | Collected information | Selected information |
|-------|-----------------------|----------------------|
| Success criteria from WCAG 2.1 | 1.1.1 Non-text Content 1.3.3 Sensory Characteristics 1.4.1 Use of Color 1.4.3 Contrast (Minimum) 1.4.4 Resize text 1.4.5 Images of Text 1.4.11 Non-text Contrast 1.4.12 Text Spacing 2.1.1 Keyboard 2.1.2 No Keyboard Trap 2.4.3 Focus Order 2.4.6 Headings and Labels 2.4.7 Focus Visible 2.5.1 Pointer Gestures | 15 success criteria identified in the first stage were selected. All of them describe features to be met by statistical charts in order to fulfill the needs of users with low vision and CVD |
| Features and components of statistical charts that may act as an accessibility barrier for users with low vision or CVD when not designed properly or not following best practices | Information Titles [19, 42], axes [19, 42], scale and legends [42], labels [42], captions [44, 45, 47, 50], abbreviations [23], details of the statistical analysis [23], data source [23], data table [19], short text alternative [55], long descriptions [39, 51], summary or abstract of the chart [56, 57] Presentation Font family [60, 62, 66], flush left [5, 63], letter spacing (tracking) and word spacing [64–66], not include a lot of italics, small caps or capital letters [5], font size [60], line width [5], syllabification [5], space following elements [5], zoom [5], customization [5], safe colors [72, 74–78], image quality [23], print version [5] Behavior Tooltips [79, 80], sonification [80, 83–86] | All the aspects considered in the literature review, which were introduced in Sects. 3.1.1, 3.1.2 and 3.1, were evaluated as relevant and included in the selection. However, given the large number of features collected the authors envisage the need to aggregate or unify some of them in a unique indicator |
| Feature          | User profile | Category   | WCAG success criteria | [16] | [20] | [15] | [17] | [28] |
|------------------|--------------|------------|-----------------------|------|------|------|------|------|
| Title            | Any user     | Good practices | 2.4.2. Page Titled   | Provide navigation tools and orientation information in pages to maximize accessibility and usability |
|                  |              |            |                       | 6–12-word descriptive title is left-justified in upper left corner |
| Axes             | Any user     | Good practices | –                     | Text size is hierarchical and readable |
|                  |              |            |                       | Text is horizontal |
|                  |              |            |                       | Labels are used sparingly |
|                  |              |            |                       | Axes intervals are equidistant |
|                  |              |            |                       | Axes do not have unnecessary tick marks or axes lines |
|                  |              |            |                       | Graph has one horizontal and one vertical axes |
| Scales           | Any user     | Good practices | –                     | Labels are used sparingly |
|                  |              |            |                       | Proportions are accurate |
|                  |              |            |                       | Data are labeled directly |
| Legend           | Any user     | Good practices | –                     | Data are labeled directly |
|                  |              |            |                       | Labels are used sparingly |
| Labels           | Any user     | Text alternatives | –                     | Subtitle and/or annotations provide additional information |
| Caption          | Any user     | Good practices | –                     | Subtitle and/or annotations provide additional information |
| Abbreviations    | Any user     | Good practices | 3.1.4 Abbreviations  | H5: Provide semantics for structure |
|                  |              |            |                       | H6: Language and readability |
|                  |              |            |                       | Acronyms and abbreviations without expansions |
| Details of the statistical analysis | Any user | Good practices | –                     | – |
|                  |              |            |                       | – |
|                  |              |            |                       | – |

Table 3 Matches among detected features, user profile who benefits from it and existing heuristics
| Feature          | User profile* | Category      | WCAG success criteria | [16] | [20] | [15] | [17] | [28] |
|------------------|---------------|---------------|-----------------------|------|------|------|------|------|
| Data source      | Any user      | Good practices|                       | –    | –    | Text size is hierarchical and readable | –    | –    |
|                  | Screen reader users | Text alternatives | 1.1.1 Non-text Content | Provide text (including text equivalents) | –    | H10: Visual and auditory alternatives | Data tables with no structural relationships | –    |
| Short alternative text | Screen reader users | Text alternatives | 1.1.1 Non-text Content | Provide text (including text equivalents) | –    | H10: Visual and auditory alternatives | Image maps Functional images lacking text Rich images lacking equivalent text | –    |
| Long description | Screen reader users | Text alternatives | 1.1.1 Non-text Content | Provide text (including text equivalents) | –    | H10: Visual and auditory alternatives | Image maps Functional images lacking text Rich images lacking equivalent text | –    |
| Abstract         | Screen reader users | Text alternatives | 1.1.1 Non-text Content | Provide text (including text equivalents) | –    | H10: Visual and auditory alternatives | Functional images lacking text Rich images lacking equivalent text | –    |
| Font family      | Any low vision user | Legibility    | 1.4.8 Visual Presentation | –    | –    | H5: Contrast and legibility | –    | –    |
| Alignment        | Any low vision user | Legibility    | 1.4.8 Visual Presentation | –    | 6–12-word descriptive title is left-justified in upper left corner | H5: Contrast and legibility | –    | –    |
| Word and letter spacing | Any low vision user | Legibility    | 1.4.12 Text Spacing | –    | –    | H5: Contrast and legibility | –    | –    |
| Italic and small caps | Any low vision user | Legibility    | 1.4.8 Visual Presentation | –    | –    | – | – | – |
| Line width       | Any low vision user | Legibility    | 1.4.8 Visual Presentation | –    | –    | Excessively long lines of text | –    | –    |
| Feature                  | User profile | Category | WCAG success criteria | [16] | [20] | [15] | [17] | [28] |
|-------------------------|--------------|----------|-----------------------|------|------|------|------|------|
| Syllabification         | Any low vision user | Legibility | 1.4 Distinguishable   | –    | –    | –    | –    | –    |
| Spacing following elements | Any low vision user | Legibility | 1.4.12 Text Spacing | –    | –    | H6: Language and readability | –    | –    |
| Zoom                    | Any low vision user | Legibility | 1.4.4 Resize text     | –    | –    | –    | Text cannot be resized | H3: User control and freedom |
| Personalization         | Any low vision user | Additional features | 1.3 Adaptable   | Allow configuration and custom H3: Provide user control for presentation by separating it from the rest of the content | – | – | – | H3: User control and freedom |
| Images of text          | Any low vision user | Legibility | 1.4.5 Images of Text | Separate structure from presentation H3: Provide user control for presentation | – | H5: Contrast and legibility | Functional images embedded in the background Functional images lacking text | – |
| Image quality           | Any low vision user | Legibility | 1.4.5 Images of Text | – | – | – | – | – |
| Safe colors             | CVD users     | Color and contrast | 1.4.1 Use of Color | Create documents that work even if the user cannot see and/or hear H2: Provide means to select equivalent content | Color is legible for people with colorblindness H5: Contrast and legibility | Color is necessary | – |
| Contrast                | Contrast sensibility users | Color and contrast | 1.4.3 Contrast (Minimum) | Create documents that work even if the user cannot see and/or hear H2: Provide means to select equivalent content | Text sufficiently contrasts background H5: Contrast and legibility | Insufficient visual contrast | – |
| Non-text Contrast       | Contrast sensibility users | Color and contrast | 1.4.11 Non-text Contrast | Create documents that work even if the user cannot see and/or hear H2: Provide means to select equivalent content | – | H5: Contrast and legibility | Insufficient visual contrast | – |
| Feature          | User profilea | Category       | WCAG success criteria                          | [16]                      | [20]                      | [15]                      | [17]                      | [28]                      |
|------------------|---------------|----------------|-----------------------------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|
| Focus visible    | Any low vision user | Legibility     | 2.4.7 Focus Visible                          | Create documents that work even if the user cannot see and/or hear | –                         | H2: Navigation and wayfinding | –                         | –                         |
| Print version    | Any user      | Good practice  | –                                             | H3: Provide user control for presentation by separating it from the rest of the content | Color is legible when printed in black and white | –                         | –                         | –                         |
| Tooltips         | Any user      | Text alternatives | 1.1.1 Non-text Content 1.4.13 Content on Hover or Focus | Provide text (including text equivalents) | –                         | H3: Structure and semantics | Excessively long tooltips | H10: Help and documentation |
| Sonification     | Screen reader user | Additional features | –                                             | Create documents that work even if the user cannot see and/or hear | –                         | –                         | –                         | –                         |
| Keyboard Accessible | Screen reader user | Additional features | 2.1.1 Keyboard 2.1.2 No Keyboard Trap | Create documents that do not rely on one type of hardware | H1: Interactions methods and modalities | Keyboard traps | –                         | –                         |
| Focus order      | Screen reader user | Additional features | 2.4.3 Focus Order | Provide understandable mechanisms for navigating within and between pages | –                         | H2: Navigation and wayfinding | –                         | H1: Visibility of system status |
3.6 Specification stage

In the specification stage, the indicators obtained in the previous stages were formally defined. As a result of this definition, a total of 17 heuristic principles were obtained. Tables 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, and 21 show the formal specification of the new set of heuristics using an adaptation of the template suggested by Quiñones et al. [38].

Every evaluator will proceed to run the individual heuristic analysis reviewing the applicability of each heuristic. Each indicator will be scored on a 7-point Likert scale (from 0 to 6) [90], where respondents will be asked how much they agree or disagree with a set of statements, following the compliance levels shown in Table 22.

Additionally, “Not Applicable” has been added to be used when the heuristic indicator is not suitable for the evaluated chart, as for example when a chart is black and white, and the heuristic is related to color hue.

In accordance with Pearce [91], there are substantial differences between the use of a more or less granular Likert scale in terms of number of statements. While a less granular scale allows for faster responses and clearer categories, it can also result in more bias or in frustration for the evaluators because their option is not represented on the scale. On the other hand, a highly granular Likert scale is more likely to have inclusive and exhaustive categories, and allows the collection of more precise data and more meaningful statistical results, with higher reliability and validity, and reduces the neutral and “uncertain” responses. However, with more granular scales, there is an associated complexity with the linguistic labels associated with each category, and the differentiation between them is not as clear. The psychometric literature suggests that having more scale points is better but that there is a diminishing return after around 11 points [92] and Sauro and Lewis [93] suggested that having seven points tends to be a good balance between having enough
| ID | Heuristic name/explanation | Action | Set of existing heuristics/guidelines | Applicability |
|----|----------------------------|--------|--------------------------------------|--------------|
| H1 | The chart should have a brief and descriptive title in order to identify its content | Adapt | [12, 15, 16, 20, 28] | (1) Useful |
| H2 | The axes labels describe the range of values of the variable or the different existing categories | Combine with H3 | [20] | (1) Useful |
| H3 | There is additional information about the axe’s scales | Combine with H2 | [20] | (1) Useful |
| H4 | There is a legend to describe the encoding mapping, such as color schemes, sizes, etc. that help users to interpret the marks | Create | – | (1) Useful |
| H5 | Labels Eliminate. Covered by H11 | – | – |
| H6 | There is a caption giving additional information about the chart in order to better understand the message and intention of the chart. It does not replicate the title | Create | – | (1) Useful |
| H7 | Abbreviations are developed both apparently and on the code | Adapt | [12, 15–17, 28] | (1) Useful |
| H8 | Statistical analysis details | Combine with H6 | – | (1) Useful |
| H9 | There is information about data source somewhere in the chart | Create | [20] | (1) Useful |
| H10 | Data is offered as a table, as an alternative to the chart | Combine with H12 | [12, 15, 16] | (3) Critical |
| H11 | The chart includes an alternative text, coded within the alt attribute, which briefly describes its content, and which acts as an identifier within a page with other charts or images | Adapt | [12, 15–17] | (1) Useful |
| H12 | The chart includes some type of long description, describing comprehensively its content, with the same purpose and offering the same information. If pertinent, this long description includes a table with all the chart data | Adapt | [12, 15–17] | (3) Critical |
| H13 | Summary Eliminate. Covered by H12 | – | – |
| H14 | Font family should be suitable for users with low vision | Combine with H15–H20 | [12, 15] | (2) Important |
| H15 | Text is aligned to the left | Combine with H14, H16–H20 | [12, 15, 20] | (2) Important |
| H16 | Leading will be at least 1.12×font size and word spacing will be at least 1.16×font size | Combine with H14–H15, H17–H20 | [12, 15] | (2) Important |
| H17 | Do not overuse italics or small caps | Combine with H14–H16, H18–H20 | [12] | (2) Important |
| H18 | Ensure optimal line length for readability | Combine with H14–H17, H19–H20 | [12, 17] | (2) Important |
| H19 | Avoid syllabification | Combine with H14–H18, H20 | – | (2) Important |
| H20 | White spaces and margins are sufficient to differentiate the different elements of the chart and for easy reading | Combine with H14–H20 | [12, 15] | (2) Important |
| H21 | After zooming the chart until 200%, using common web browser tools, the chart should be legible without horizontal scroll | Adapt | [12, 17, 28] | (2) Important |
| H22 | Customization options for font size, color, contrast and other perceptual properties of the chart should be offered, or at least permitted | Adapt | [16, 28] | (2) Important |
| H23 | Images of text Eliminate | – | – |
| H24 | Bitmap images should offer a sufficient quality level | Create | [12] | (3) Critical |
| H25 | There are at maximum 5 safe colors to encode categorical or qualitative variables. Alternatively, the chart uses patterns or textures as encoding | Adapt | [12, 15–17, 20] | (3) Critical |
| H26 | Contrast between text and background has a ratio of at least 4.5:1 | Combine with H27 | [12, 15–17, 20] | (3) Critical |
points for discrimination without having to maintain too many response options.

After scoring, heuristics are weighed depending on their impact or severity into 3 levels: low impact (1), average impact (2), high impact (3). To decide which weight each indicator would have, the authors relied on the “Applicability” column of Table 4, from the selection stage. For a detailed description of each level impact the reader may refer to Table 23. It is worth mentioning that these three levels are not related to the three levels of conformity within WCAG.

The score in the Likert scale is multiplied by the weight resulting in a weighted value, for every indicator. This obtained value is multiplied by 10. At the same time the maximum weighted value of the overall chart is calculated, taking into account that the maximum score for the “Not
Applicable” indicator is 0, and 6 for all the others. Then the maximum is used to divide the previous number.

3.7 Validation stage

The objective of the validation stage was to check the adequacy of the set of heuristic indicators taking into account their efficiency, via different experiments. Quiñones et al. [38] offer several options to validate the set of heuristics: validation through heuristic evaluation, validation through expert judgment and validation through user testing. In this research, the validation consisted of two experiments where four evaluators (the authors of the paper plus one experienced evaluator) assessed the charts using heuristic evaluation methodology.

After compiling a list and brief description of each heuristic, three evaluators carried out the first round of evaluations of a sample of 9 HTML charts appearing in the websites of two Catalan universities and in the Catalan University Quality Assurance Agency website [94] based on this list. This first experiment, which was more informal, acted like a training session on the methodology and helped the evaluators to become acquainted with the set of heuristics. After this experiment, the evaluators realized that assigning a score just by its value was too subjective and decided to enhance the description of every heuristic with a guide on how to assign scores. In this sense, the specification of each heuristic was complemented with a brief indication on how to meet it and with a checklist of aspects that should be observed during the evaluation. These new elements are detailed in the refinement stage (Table 24).

The second experiment, more formal, consisted of evaluating a sample of 35 statistical charts published in the digital version of the 5 newspapers with the biggest audience.

### Table 7 H3. Axes heuristic

| ID | 3 |
|----|---|
| Priority | (1) useful |
| Name | Axes |
| Category | Good practices |
| Understanding the heuristic | This heuristic seeks to ensure that chart axes (time, categories, values) are included in the chart and that axes labels are suitable and clear. Labels should be offered as actual text and not as an image of text |
| Benefits | User profile who benefits: any user |
| Axes help understand the data |

### Table 8 H4. Caption heuristic

| ID | 4 |
|----|---|
| Priority | (1) useful |
| Name | Caption |
| Category | Good practices |
| Understanding the heuristic | This heuristic seeks to ensure that there is a caption for each chart. The caption should contribute to the understanding of the chart |
| Benefits | User profile who benefits: any user |
| Chart caption, far from duplicating information, helps understanding the message communicated by the chart, offers a synthesis of the most relevant data and may also offer some conclusion or additional information |

### Table 9 H5. Abbreviations heuristic

| ID | 5 |
|----|---|
| Priority | (1) useful |
| Name | Abbreviations |
| Category | Good practices |
| Understanding the heuristic | This heuristic seeks to ensure that all abbreviations are developed to help understanding |
| Benefits | User profile who benefits: any user |

### Table 10 H6. Data source heuristic

| ID | 6 |
|----|---|
| Priority | (1) useful |
| Name | Data source |
| Category | Good practices |
| Understanding the heuristic | This heuristic seeks to ensure that the chart informs about the data source |
| Benefits | User profile who benefits: any user |

\[
(\sum_{i=1}^{n} \text{assigned score} \times \text{weight}) \times 10 \over \sum_{i=1}^{n} \text{maximum score} \times \text{weight}
\]
in Spain (El País, El Mundo, ABC, El Periódico and La Vanguardia), and in 2 international newspapers that are widely recognized as being good at information visualization (The New York Times and The Guardian) [95]. In this case, the analyzed sample contained both vector and bitmap charts. The selected newspapers were reviewed thoroughly during October 2019, and a sample of 5 charts was chosen from each one. Bar and line charts were the most common types of chart included; some pie charts were also included since, although their use is controversial, they are still a common chart, and the sample also contained a few variations of bar and line charts, which are also in widespread use. The exact

Table 11  H7. Print version heuristic

| ID | 7 |
| Priority | (1) useful |
| Name | Print version |
| Category | Good practices |
| Understanding the heuristic | This heuristic seeks to ensure a printed version of the chart, optimized for this medium, to those users who may prefer applying it |
| Benefits | User profile who benefits: any user Having an optimized version for printing, allows users with low vision, to print it and avoid having to consult the screen with forced positions near the screen |

Table 12  H8. Short text alternative heuristic

| ID | 8 |
| Priority | (1) useful |
| Name | Short text alternative |
| Category | Text alternatives |
| Understanding the heuristic | This heuristic seeks to ensure that every chart has an alternative text which briefly informs about the contents of the chart and help users decide if they want more information about it. If there is a long description associated to the chart (see heuristic 9) this text informs about it |
| Benefits | User profile who benefits: screen reader users |

Table 13  H9. Long description heuristic

| ID | 9 |
| Priority | (3) Critical |
| Name | Long description |
| Category | Text alternatives |
| Understanding the heuristic | This heuristic seeks to ensure that every complex chart offers a textual long description giving the same information as the chart |
| Benefits | User profile who benefits: screen reader users |

Table 14  H10. Safe colors heuristic

| ID | 10 |
| Priority | (3) Critical |
| Name | Safe colors |
| Category | Color and contrast |
| Understanding the heuristic | This heuristic seeks to ensure that users with different profiles of CVD can differentiate colors used in the chart |
| Benefits | User profile who benefits: low vision and CVD users |

Table 15  H11. Contrast heuristic

| ID | 11 |
| Priority | (3) Critical |
| Name | Contrast |
| Category | Color and contrast |
| Understanding the heuristic | This heuristic seeks to ensure perception of the different elements of the chart |
| Benefits | User profile who benefits: users with low contrast sensitivity |
distribution was: bar charts (14), line charts (13), pie charts (4), stacked bar charts (2), combined bar and line charts (1), and dot diagrams (1).

The results of the evaluation of each statistical chart were recorded using a specific custom-made template, which automatically calculated the final score. Each evaluator was given an Excel template for the evaluation of each chart. The template included a screenshot of the chart and its URL on sheet 1; questionnaire for scores on sheet 2 that also included a field for the evaluator to briefly describe the problems associated with each indicator; the final score was automatically calculated on sheet 3. Each evaluator carried out their evaluation independently and a final meeting was held to review everything, particularly the discrepancies. Charts were evaluated only once, and the standard deviation between scores for the same charts were calculated; this was helpful for detecting special cases to discuss. When a discrepancy occurred (a deviation higher than 2), the evaluators went deeper into the specific criteria used for scoring. The researchers did not detect any learning effect because they did not impose any order on the evaluation nor did they record the order each evaluator followed. In future experiments, the authors may consider measuring the learning

| Table 16 | H12. Legibility heuristic |
|----------|---------------------------|
| ID       | 12                        |
| Priority | (2) Important             |
| Name     | Legibility                |
| Category | Legibility                |
| Understanding the heuristic | This heuristic seeks to ensure that all text included in the chart or accompanying it follows typographical and layout principles that foster legibility |
| Benefits | User profile who benefits: any user with low vision |

| Table 17 | H13. Image quality heuristic |
|----------|-----------------------------|
| ID       | 13                         |
| Priority | (3) Critical               |
| Name     | Image quality (bitmaps)    |
| Category | Legibility                 |
| Understanding the heuristic | This heuristic seeks to ensure that all charts, and in particular bitmaps, offer a sufficient quality for a clear visualization and also support a zoom of at least 200% without blurring or pixelation |
| Benefits | User profile who benefits: any low vision user |

| Table 18 | H14. Resize heuristic |
|----------|------------------------|
| ID       | 14                     |
| Priority | (2) Important          |
| Name     | Resize                 |
| Category | Legibility             |
| Understanding the heuristic | This heuristic seeks to ensure that the chart can be zoomed in until 200% without the need of any assistive tool and where zoomed all the content can be seen, there is no overlap and all original functionalities are available |
| Benefits | User profile who benefits: any low vision user |

| Table 19 | H15. Focus visible heuristic |
|----------|-----------------------------|
| ID       | 15                         |
| Priority | (1) Useful                 |
| Name     | Focus visible              |
| Category | Legibility                 |
| Understanding the heuristic | This heuristic seeks to ensure that when an element of the chart receives the mouse or the keyboard focus, there appears some visible indication |
| Benefits | User profile who benefits: any low vision user |
effect together with the time taken for each evaluation in order to assess the practicality of the evaluation method.

The main accessibility problems detected by the evaluators were: the almost total lack of textual alternatives in the charts in bitmap format, a problem also found in SVG charts, in which standards such as WAI-ARIA were not used to label the marks (24 out of 35 bitmap and SVG charts); the use of insufficient or incorrect text alternatives when they were included (6 out of 11 charts with alt text); the poor use of visible indicators to highlight the elements that were the focus of the charts (9 out of 11 SVG charts); not supporting a keyboard interface (11 out of 11 SVG charts); an insufficient non-text contrast ratio in many of the analyzed charts (26 out of 35 charts); the use of a font size that was too small (35 out of 35 charts); and the non-systematization of the use of safe color palettes for people with CVD, which was a widespread practice, except in *The New York times* and *The Guardian*, which mainly complied with this requirement.

Based on these results, we can conclude that some of the problems detected by the evaluators in the experiments conducted during the validation stage were similar to the problems found by other authors (use of insufficient or incorrect text alternatives when they are included, the use of a font size that is too small and the non-systematization of the use of safe color palettes for people with CVD) [24, 25]. Beyond these known problems, the set of heuristics proposed was not only practical and applicable to the domain, but also allowed the identification of additional problems not previously highlighted in the literature.

In this stage, the methodology was complemented and enriched by the calculation of several quality metrics proposed by Jiménez et al. [37]. Compared to the metrics proposed by Quiñones et al. [38], those of Jiménez et al. are more easily quantified and ready to use through their corresponding formulas, giving the validation a more solid basis.

### Table 20 H16. Device independent navigation heuristic

| ID | 16 |
|----|----|
| Priority | (3) Critical |
| Name | Device independent navigation |
| Category | Additional features |
| Understanding the heuristic | For dynamic charts, this heuristic seeks to allow users to navigate between the marks and elements of the chart with keyboard, mouse or gestures |
| Benefits | User profile who benefits: low vision and screen reader users. Also, for users with motor disabilities Users can navigate through the marks, data labels, legends, axes, although they cannot use devices such as mouses that require eye-hand coordination, have trouble finding or tracking a pointer indicator on screen or have tremors using a mouse |

### Table 21 H17. Personalization heuristic

| ID | 17 |
|----|----|
| Priority | (2) Important |
| Name | Personalization |
| Category | Additional features |
| Understanding the heuristic | This heuristic seeks to allow users to customize the chart, by modifying the color scheme, the contrast or the text (font family, font size, line height, etc.) |
| Benefits | User profile who benefits: low vision and CVD Customization is useful to ensure a good level of accessibility to a user profile as diverse as the low vision users |

### Table 22 Likert scale

| Score | Level of compliance |
|-------|---------------------|
| – | Not applicable (NA) |
| 0 | No compliance |
| 1 | Very low compliance |
| 2 | Low compliance |
| 3 | Acceptable compliance |
| 4 | High compliance |
| 5 | Very high compliance |
| 6 | Excellent compliance |

### Table 23 Weighting criteria for indicators

| Criteria | Weight |
|-----------|--------|
| If the chart fails the heuristic, one or more user profiles will not have a satisfactory user experience with the chart, mildly compromising its accessibility | \( \times 1 \) |
| If the chart succeeds at the heuristic the chart accessibility slightly improves | |
| If the chart fails the heuristic, one or more user profiles will have serious difficulties to perceive the chart information, severely compromising its accessibility | \( \times 2 \) |
| If the chart succeeds at the heuristic the chart accessibility considerably improves | |
| If the chart fails the heuristic, one or more user profiles will not be able to perceive the chart information, totally compromising its accessibility | \( \times 3 \) |
| This heuristic is key to provide access to the chart for one or more profiles | |
| Heuristic | How to meet the heuristic | Checklist |
|-----------|---------------------------|-----------|
| H1        | Complement the chart with a brief but descriptive title, preferably in text and not as an image | There is a title for the chart  
The title is brief and descriptive  
The title offers a first approximation to the content of the chart and differentiates this chart from others appearing on the same page  
The title is actual text and not an image of text |
| H2        | Include a legend which univocally associates color schemes, patterns, sizes or shapes used in the chart with their respective value. Offer the legend as actual text and not as an image of text | The chart offers an external legend or labels near every category mark  
The legend explains the encoding used in the chart  
The legend is offered as actual text and not as an image of text |
| H3        | Axes should be visible. They should include labels  
Each axis should have a concise but sufficiently descriptive title. When pertinent this title must include the used units and the precision (i.e. thousands of gallons, millions of years…) | Necessary axes are included  
Axes have labels |
| H4        | If the chart is very simple skip this requirement. In this case, not having a caption does not cause any difficulty. If the chart is a bit more complicated, write a caption for the chart synthesizing the message communicated by the chart. The caption should be offered as actual text and not as an image of text | The chart has a caption  
The caption does not replicate the title. It provides additional information  
If appropriate, the chart includes details of the statistical analysis (standard deviation, p value, etc.)  
Caption is offered as actual text and not as an image of text |
| H5        | To use `<abbr>` element and put the full form in the code  
To relate the abbreviation with its complete wording through a link | Abbreviations are developed following a standard method supported by assistive tools  
Developed forms are written as actual text and not as an image of text |
| H6        | Preferably near the caption, the source (institution and dataset), date and also a link to it are given | Somewhere in the chart, preferably near the caption, there is information about the data source  
The data source identifies the institution and links to the dataset where the data come from  
The data source is actual text and not an image of text |
| H7        | Printing of the page containing the chart should be able to be visualized correctly. This is ensured through CSS styles  
A version for specific printing optimized is offered outside the browser’s native print options | Users can print the chart in a version specifically optimized for this medium  
The printed version has a good legibility  
The printed version has a good legibility, even when printed on black and white |
| H8        | The most common way to reach the goal of this heuristic is using the "alt" attribute inside the `<img>` element. When the chart is coded in SVG, alternative texts can be written directly within the chart. Sometimes the attribute "aria-labelledby" can be used for this purpose | The chart has an alternative text  
The chart has an alternative text, the alternative text is brief and descriptive  
The alternative text is not redundant with the title |
| H9        | Using the "longdesc" attribute, with a link to the long description which should be available, preferably, on the same page as the chart  
Offering a link near the chart with a link to the long description  
Giving the location of the long description within the alt attribute  
Using the `figcaption` element, to include both the chart and the description  
Giving the description just after the chart. This is the preferred option  
A correct long description gives an abstract of the message conveyed by the chart, a data table with the values present in the chart and information about the display (used marks, axes, encodings…) | The long description provides detailed information about what is presented visually, including scales, values, relationships and trends  
The data values are provided through a data table  
The chart is structurally associated with the long description |
| H10       | To reach the goal of this heuristic the color scheme should be safe for the different types of chromatic vision deficiencies, including achromatopsia (total absence of color vision) | There is a maximum of 5 safe colors to differentiate qualitative, ordinal or quantitative variables  
Alternatively, values are differentiated by patterns or textures. The chart is seen correctly for protanopia, deuteranopia, tritanopia and achromatopsia profiles. This can be checked with a simulation tool such as NoCoffee® |
| H11       | The visual presentation of text and images of text has a contrast ratio of at least 4.5:1"  
The visual presentation of parts of graphics required to understand the context have a contrast ratio of at least 3:1" | Ensuring that a contrast ratio of at least 4.5:1 exists between text (and images of text) and background behind the text. Also ensuring that a contrast ratio of at least 3:1 exists between text (and images of text) and background behind the text. This can be checked with a tool such as Colour Contrast Analyser (CCA)® |
### Table 24 (continued)

| Heuristic | How to meet the heuristic | Checklist |
|-----------|---------------------------|-----------|
| H12       | In order to reach the goal of this heuristic, labels, captions, tables and descriptions are written on a suitable font family, use a correct font size and avoid overusing capitals, small capitals or italics. Line, letter and word spacing should also be adequate for legibility | Text uses a font family suitable for low vision (Sans Serif). For example: Arial, Helvetica, Courier or Verdana, or fonts designed for low vision such as APHont or Eido. Although the recommended font size for legibility is 16px, on charts this is an almost impossible requirement. Kerning and word spacing should be enough, line spacing should be 1.5. This heuristic is related to H14 which requires zooming without losing of quality. Text should be left aligned. Lower characters and regular style are preferably used. |
| H13       | In order to reach the goal of this heuristic, authors should pay attention to image size, resolution, bit depth, and format | Image size (number of pixels): should be sufficient for a zoom of 200% without blurring or pixilation. Format: PNG preferably, or JPG with a suitable level of compression. Resolution: 150 ppi as a minimum. Bit depth: 8 to 32 bits. |
| H14       | This heuristic means users can zoom in the chart with browser tools and that in doing so the layout is still logical, and all features of the chart are viewable and all functionalities available. In order to make the chart more adaptable it is recommended to use relative units (em, rem, percentages, etc.) instead of absolute units (pt, px, etc.) | When a chart is zoomed in 200% there are not overlapped elements. Should be legible without horizontal scroll. |
| H15       | The most common approach to reach this goal is using CSS to change the presentation of the elements when receiving focus. This criterium only applies to vectorial charts or charts implemented with JavaScript libraries, not to bit-maps, because in these no element is able to receive the focus. | On a vectorial chart when an element receives the focus of the keyboard or the mouse, the element is highlighted in some way. |
| H16       | All events or interactions available on the chart should be device independent. This criterium only applies to vectorial charts or charts implemented with JavaScript libraries, not to bit-maps, because in these no element is able to receive the focus. | Navigate through the chart with the keyboard, mouse, and gestures. |
| H17       | In order to reach this goal, the chart must follow the standards, for assistive technology with customization possibilities and support them. Alternatively, this goal can be reached, through a custom-made personalization system. | Review if the chart offers customization options. Use some assistive tool or a browser extension to personalize style sheets and test if it is possible to modify the chart. |

a The reference for the recommended value is the success criterion 1.4.3 (contrast minimum) of the WCAG. More information available at: [https://www.w3.org/WAI/WCAG21/Understanding/contrast-minimum.html](https://www.w3.org/WAI/WCAG21/Understanding/contrast-minimum.html)
b The reference for the recommended value is the success criterion 1.4.11 (non-text contrast) of the WCAG. More information available at: [https://www.w3.org/WAI/WCAG21/Understanding/non-text-contrast.html](https://www.w3.org/WAI/WCAG21/Understanding/non-text-contrast.html)
c [https://accessgarage.wordpress.com/2013/02/09/458/](https://accessgarage.wordpress.com/2013/02/09/458/)
d [https://www.tpgi.com/color-contrast-checker/](https://www.tpgi.com/color-contrast-checker/)
e [https://mediaarea.net/](https://mediaarea.net/)
Jiménez et al. [37] suggested the use of several indicators to compare domain heuristics (d) with control heuristics (c). Domain heuristics refers to the final heuristics created during the process (Tables 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 and 21) and control heuristics refers to the initial heuristics identified during the exploratory stage. In this research, 14 WCAG 2.1 relevant success criteria level A and AA were selected as the set of control heuristics (Table 1).

Ratio of unique problems. The relation of unique problems (that is, the number of different problems found) identified by the new set of heuristics in comparison with the control heuristics. If the ratio is bigger than 1 the new set identifies more unique problems:

$$\Phi_p = \frac{P_d}{P_c}$$

Ratio of problem dispersion. The distribution of problems identified by each heuristic in the new set of heuristics in comparison with the control heuristics. If the ratio is bigger than 1 the new set has a more equilibrated distribution:

$$\delta_p = \frac{\delta c}{\delta d}$$

Ratio of severity. The severity of problems identified with the new set of heuristics in comparison with the control heuristics. If the ratio is bigger than 1, the new set identifies more severe problems. For this ratio the researchers used the severity assigned to the new set of heuristics: (1) Useful, (2) Important and (3) Critical, and the severity assigned by WCAG: 3 (A), 2 (AA) and 1 (AAA):

$$\lambda_p = \frac{\lambda d}{\lambda c}$$

Ratio of specificity. The specificity of problems identified with the new set of heuristics in comparison with the control heuristics. If the ratio is bigger than 1 the new set identifies more specific problems. To apply this ratio, two levels of specificity were established: the first level is assigned to the problems that apply to any type of website or application, and the second for those problems that only apply to statistical charts:

$$\varepsilon_p = \frac{\varepsilon d}{\varepsilon c}$$

The results for the indicators in this sample after the second evaluation was conducted [95] are:

- Ratio of unique problems: \(340/134 = 2.54\), where 340 refers to the unique problems detected by the domain heuristics and 134 to the unique problems detected by the control heuristic. The ratio is much bigger than 1 and clearly indicates that the new set identified many more unique problems;
- Ratio of problem dispersion: \(0.68/0.45 = 1.52\), where 0.68 is the standard deviation of the number of problems associated with each of the domain heuristics and 0.45 is the standard deviation of the control heuristics. The ratio is bigger than 1, indicating that the distribution of the final heuristics is relatively equilibrated;
- Ratio of severity: \(0.76/0.71 = 1.07\), where 0.76 is the mean severity of the problems detected by the domain heuristics and 0.71 is the mean severity of the problems detected by the control heuristics. The ratio is slightly greater than 1, which means that the new set of heuristics identified slightly more severe problems;
- Ratio of specificity: \(1.27/1 = 1.27\), where 1.27 is the mean specificity of the problems detected by the domain heuristics and 1 is the mean specificity of the problems detected by the control heuristics. The ratio is bigger than 1 as expected, because in WCAG there are many heuristics applying to general problems.

The previous metrics were calculated by the researcher in charge of the statistical analysis (RA) during the validation process. With these indicator values, we can conclude that the proposed heuristics identify more unique problems, the problems are better distributed, more severe and specific than in the control set, and therefore the new set of heuristics is much more suitable for evaluating the accessibility of statistical charts.

### 3.8 Refinement stage

The objective of the final stage (refinement) was to refine and verify the set of indicators based on the conclusions or comments resulting from the previous stage (validation).

11 Data available at: [https://www.ub.edu/adaptabit/charts-accessibility/press/heuristics_validation.xlsx](https://www.ub.edu/adaptabit/charts-accessibility/press/heuristics_validation.xlsx).
After the two experiments [94, 95], a meeting was held to reflect on the methodology. As a conclusion of this meeting several descriptions were improved (Table 24), the researchers decided to use a shorter Likert scale (Table 25) as it was difficult to fine grain the score, and one indicator was added, i.e. H15 (Table 27), related to a new accessibility problem detected during the evaluations (see Sect. 3.8.3).

A detailed explanation of the findings and decisions taken during this meeting follows.

### 3.8.1 Clarity of indicators

Some indicators were not entirely clear to all evaluators who had to conduct consultations during the evaluation process. For this reason, before the second experiment, additional information about each heuristic was added. For each heuristic principle, an additional checklist was developed with a list of items that must be checked (Table 24).

### 3.8.2 Ease of performing the heuristic evaluation

The evaluators stated that they were comfortable with the indicators and the proposed evaluation methodology, but some evaluators argued that a new level of compliance in the Likert scale to indicate that failing is not a problem was necessary, for example, when the abbreviations are not developed, but are commonly used and well known by the audience.

Furthermore, all the evaluators agreed about the difficulty of applying a 7-point Likert scale. In this sense, it was proposed to use a scale of 5 points (Table 25). Some evaluators also agreed on the usefulness of having a scale with reference values to assign the score of each indicator and the authors are now working on a guidance document including this. This is easily applicable to some indicators that evaluate objective problems such as image low resolution or bit depth, but somewhat more complex when it comes to assessing more subjective aspects such as the adequacy of a title or a text alternative.

### 3.8.3 Completeness of heuristics set

The evaluators agreed that the heuristics contemplated were sufficient to carry out the evaluation and to detect all the accessibility problems present in the analyzed graphics, with the exception of an identified accessibility problem that could not be associated with any of them. During the evaluation, there were several charts that showed watermarks or advertising banners on the image preventing the total or partial vision of the object. Both watermarks and banners are two resources present on numerous websites, so it is likely that charts from other thematic areas also present these problems. Accordingly, it was proposed to add a new indicator.
associated with this problem. Table 26 and 27 show the process of specification of the new heuristic.

3.8.4 Lessons learned

In general, the feedback provided by the evaluators was positive. As previously discussed, the heuristic set seems sufficient to shed light on the accessibility problems of statistical charts.

One of the aspects that became apparent after the two experiments carried out in the validation stage is that charts in both bitmap and vector formats can present the same problems if they are not created following the principles of accessibility. That is, despite the initial advantage that vector charts have by not being images of text, or their compatibility with widely adopted standards such as WAI-ARIA, the reality is that, if these aspects are not taken care of, the resulting product will not be accessible. This was the case in the majority of charts analyzed, which were therefore not focused on meeting the needs of people with disabilities. In contrast, charts in bitmap format with a title, alternative texts, long descriptions and taking into account the necessary color and contrast requirements, among the other factors included in the proposed heuristic set, may be equally or even more accessible for people with low vision.

Although the additional information on each heuristic collected in Table 24 is considered useful, the authors believe that having a more detailed guide, with examples of scores, will unify the evaluation criteria for evaluators. Another aspect that may be useful for new evaluators who wish to use the set of indicators proposed in this work is the availability of some examples of evaluations carried out on a set of charts that present the most common accessibility problems of the domain under study.

4 Results

In this research, the authors introduced a new accessibility tool: a heuristic checklist complementary to WCAG and focused on the accessibility of statistical charts for people with low vision and people with CVD. The indicators included in this work, as well as the developed tool, are a contribution to the evaluation of charts accessibility with a special focus on people with low vision and people with CVD which tries to compensate a lack of research in guidelines, standards and even recommendations for low vision people, who still benefit from some residual sight.

As a result of the methodology developed by Quiñones et al. [38] a set of 18 heuristics has been created. It has been validated with an experimental evaluation of 35 statistical charts and with the validation method proposed by Jiménez et al. [37]. The evaluation with charts helped identify many problems and some good practices. The validation following the procedure by Jiménez was very positive and all indicators revealed that the proposed set is more effective and efficient than the control heuristics.

The heuristics cover the range of needs of the different low vision and CVD profiles (see Table 28), and also include general best practices that benefit any user.

The main result of this research is the list of heuristics obtained that is fully described in Sects. 3.6 Specification stage and slightly modified in Sect. 3.8 Refinement stage.

5 Discussion

Increasing efforts are being made to take into account the difficulties of different disability groups and providing them with accessible solutions, but there are some often forgotten groups such as cognitive impaired users or users with low vision. In particular, there is a lack of knowledge of low vision as a disability, both by institutions and large companies which causes this group not to be included when trying to address the barriers of access for people with visual disabilities. A clear example is the fact that the native screen magnification for Android was not available until the fourth version of the operating system, while the screen reader (Google TalkBack) was included since the first versions [96]. This lack of knowledge among society and technology is gradually being reduced with a better knowledge and more accessible solutions addressed to this user group. An example in the civil sphere is the campaign “I have low vision” by Begisare association, and by Association of affected Retinitis Pigmentosa of Gipuzkoa (Spain), or the incorporation to WCAG 2.1 of a new success criteria relating non-text contrast. Summing up, this research adds to a general trend to extend accessibility to wider user groups and to more domains like STEM disciplines [97].

The authors argue the need for specialized accessibility checklists to help not only accessibility experts or practitioners but also designers, content editors, or education managers to better create and evaluate STEM content, and in particular

| User profile                        | Specific heuristics for this profile |
|-------------------------------------|-------------------------------------|
| Any user                            | 8                                   |
| Moderate low vision (screen magnifier users) | 5                                   |
| Severe low vision (screen reader)    | 3                                   |
| CVD                                 | 1                                   |
| Contrast sensitivity                 | 1                                   |
with this research, statistical charts. Heuristic checklists are not only useful for evaluation purposes, but they also serve as a guide for authors when creating new charts. Accordingly, the authors hope this tool also fulfills this additional mission and there will be an increment of accessible charts on the web.

In comparison with the WCAG and the heuristic sets proposed by Boudreau [15] and Koivunen and McCathieNevile [16], the heuristics proposed in this work are more specific. The checklist proposed by Evergreen & Emery [20] is equally specific, but it is not aimed to evaluate web accessibility, but rather the "development of high-impact data visualizations". Other initiatives, such as the Diagram Center guidelines, focus on blind and severe low vision people, and pays very low attention to the needs of low vision and CVD users.

6 Limitations and future work

One of the most critical stages when creating a set of heuristics following the methodology by Quiñones et al. [38] is validation. Among the three different tasks proposed in their methodology, validation through heuristic evaluation, validation through expert judgment and validation through user test, this research only tried the first one. Two experimental evaluations helped the research team to add a new indicator and refine the Likert scale. The research team could themselves be considered experts as they have worked with accessibility for a long time, and one of them is also working in information visualization.

Relating to user test, although users have not been included in previous research work during the creation of a set of heuristics, an actual user centered design requires them to take an active role during the process. Moreover, the research by Power et al. [98] shows that only half of the problems encountered by users are covered by WCAG, and that in some cases, even after following WCAG recommendations and techniques, the problem is not yet solved. Additionally, Lechner’s research [34] shows that users are very valuable on specific domains, as in the area we are discussed, because they contribute with a new perspective and identify problems that experts are not always able to detect. Authors are working to incorporate users within the process as an important future work direction, in order to further validate effectiveness and efficiency of the tool, and to end up with a set of heuristics which covers better the real needs of users with low vision or CVD.

While the objective of heuristic evaluations is to identify the accessibility/usability problems in a user interface [26], rather than obtaining a final score, another future line of work would be to complement the score obtained using the Likert scale by calculating the severity of the identified problems. Severity ratings can be used to prioritize the resolution of certain problems before the publication of a chart or in the process of redesigning the interface. For Nielsen [99], severity is a combination of three factors: frequency, impact and persistence. Brajnik [17] suggested considering just two of these parameters when estimating the severity of a barrier: impact and persistence. Brajnik classified problems under three categories or grades of severity, i.e., minor, significant and critical, and proposed using a scale of 1 (mild case) to 3 (worst case) for both impact and persistence to obtain the severity value. In a recent study [100], the authors incorporated these metrics to complement the purely quantitative assessment with a more qualitative approach, with interesting results, although more thought and actual users are necessary to refine the method used to rate the severity of accessibility problems with reliability.

Finally, another future line of work is the creation of tools to help evaluators while scoring a chart, looking to reduce effort and maximize harmonization between different evaluations.

7 Conclusions

The research presented shows a proposal of 18 heuristic indicators for a quantitative evaluation of the accessibility of statistical charts in the web. The set does not pretend to substitute WCAG criteria and success points because it is not linked to conformity. Nevertheless, there is a complementarity between both tools. With both not only experts but also content writers, publishers, researchers and those in charge of procuring content, with no substantial accessibility expertise, would be able to design, evaluate or choose the most suitable statistical charts to incorporate to their publications or websites.

Heuristic evaluation is a well-known and widely used usability inspection method with numerous examples published in the scientific literature. Heuristics help experts to better understand which aspects of the interface may be problematic for accessibility, and also provide them information on how to solve these problems [101]. Additionally, another benefit of heuristics is their low cost and quick application.

Statistical charts are becoming part of widespread digital literacy and are already a basic type of everyday information. Although there exist numerous proposals of general heuristics targeting usability, user experience or accessibility, the specificity of statistical charts and the particular needs of users with low vision or CVD increases the need to adapt existing indicators, and even to create new ones, in order to cover all problems related to this domain. This research is a first step in this direction and will help to create better charts.

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Declaration

Conflict of Interest  The authors declare that they have no conflict of interest.

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