Conveying Uncertainty in Data Visualizations to Screen-Reader Users Through Non-Visual Means

Ather Sharif
asharif@cs.washington.edu
Paul G. Allen School of Computer Science & Engineering | DUB Group, University of Washington
Seattle, Washington, USA

Ruican Zhong*
rzhong98@uw.edu
Human-Centered Design & Engineering | DUB Group, University of Washington
Seattle, Washington, USA

Yadi Wang*
yadiw@cs.washington.edu
Paul G. Allen School of Computer Science & Engineering | DUB Group, University of Washington
Seattle, Washington, USA

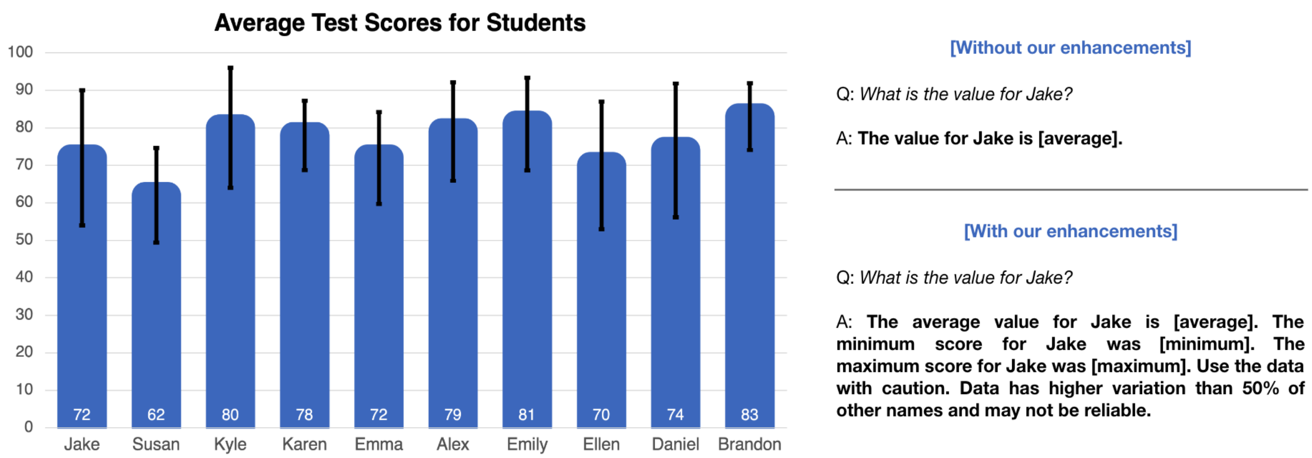

Figure 1: A screen-reader user's interaction with a data visualization of the average test scores for students. "Q" and "A" represent a question asked by a screen-reader user and the answer issued to them with and without enhancements to VoxLens, respectively. Error bars represent mean ±1 standard deviation.

ABSTRACT

Incorporating uncertainty in data visualizations is critical for users to interpret and reliably draw informed conclusions from the underlying data. However, visualization creators conventionally convey the information regarding uncertainty in data visualizations using visual techniques (e.g., error bars), which disenfranchises screen-reader users, who may be blind or have low vision. In this preliminary exploration, we investigated ways to convey uncertainty in data visualizations to screen-reader users. Specifically, we conducted semi-structured interviews, finding that these users prefer to obtain statistical information on uncertainty expressed in plain language, conveyed holistically with avenues to explore the data further in a drilled-down manner. To support screen-reader users in extracting information about uncertainty in online data visualizations, we utilized our findings to enhance VoxLens—an open-source JavaScript plug-in that makes online data visualizations accessible to screen-reader users.

*These authors contributed equally to this work.

ASSETS '23, October 22–25, 2023, New York, NY, USA

ACM ISBN 979-8-4007-0220-4/23/10.
https://doi.org/10.1145/3597638.3614502

CCS CONCEPTS

• **Human-centered computing** → **Information visualization**; **Accessibility systems and tools**; • **Social and professional topics** → **People with disabilities**.

KEYWORDS

uncertainty, visualizations, screen reader, blind, voxlens

ACM Reference Format:
Ather Sharif, Ruican Zhong, and Yadi Wang. 2023. Conveying Uncertainty in Data Visualizations to Screen-Reader Users Through Non-Visual Means. In *The 25th International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS '23), October 22–25, 2023, New York, NY, USA.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3597638.3614502

1 INTRODUCTION

"*In most cases, visualization is often thought to be an abstract visual representation of the actual information. However, that's not always possible in real-world scenarios, as no data can be sufficiently reliable and complete. There is bound to be some degree of uncertainty associated with any data*" [13]. Due to this reason, communicating the uncertainty in data visualizations is one of the top visualization research problems [12]. The visualization community has widely researched and discussed this topic [2, 4, 7, 10, 18, 25]. However, communicating uncertainty to screen-reader users via non-visual means remains unexplored, exacerbating the disenfranchisement these users face due to inaccessible data visualizations [8]. Therefore, in this work, we sought to understand and convey the data uncertainty in visualizations to screen-reader users[1].

The inaccessibility of online data visualizations causes screen-reader users to spend 122% more time interacting with and extracting information 62% less accurately from online data visualizations than non-screen-reader users [20]. Several techniques to make online data visualizations accessible exist, including alternative text [14, 15, 21], tables [5, 6], audio graphs [9, 22, 26], and verbal question-and-answer-based information extraction [23]. While Fan *et al.* [8] have briefly discussed this subject, no prior work has conveyed the uncertainty in data visualizations through non-visual means using any of these techniques, which can limit such users in making informed decisions [27]. Additionally, no prior work has explored the screen-reader users' preferences in obtaining this information. Our exploration is the first empirical work to communicate uncertainty in data visualizations to screen-reader users.

Our goal from this preliminary exploration is to create generalizable knowledge for visualization creators to communicate uncertainty in data visualizations to screen-reader users. To achieve this goal, we conducted semi-structured interviews with 16 screen-reader users. Our findings show that participants were unfamiliar with uncertainty before partaking in our user study. However, after developing a conceptual understanding of uncertainty, they expressed interest in obtaining this information holistically and granularly, in plain language, with an option to include statistical terms for expert users.

We utilized our findings to extend the functionalities of VoxLens, an open-source JavaScript plug-in that makes online data visualizations accessible using a multi-modal approach [23]. Specifically, we enabled screen-reader users to acquire information on uncertainty during their data point extraction using the *Question-and-Answer* mode of VoxLens. We used the coefficient of variation (CV) as the statistical measure to determine and convey uncertainty.

Our contributions from this work are twofold: (1) we provide empirical findings from our semi-structured interviews with 16 screen-reader users that shed light on the preferences of these users in obtaining information on uncertainty in data visualizations, and (2) we enhance the capabilities of the open-source VoxLens library to support screen-reader users in extracting uncertainty information from online data visualizations. Our open-source implementation is available at https://github.com/athersharif/voxlens.

[1]We define "screen-reader users" as users who use screen readers, temporarily or permanently, to read digital content from their computer screen, similar to the usage of this term in prior work [20, 23].

2 USER INTERVIEWS

We conducted semi-structured interviews with 16 screen-reader users to understand and convey information on uncertainty in online data visualizations via non-visual means.

2.1 Participants & Procedure

We recruited 16 screen-reader users for our study via word-of-mouth advertisement and snowball sampling (see Appendix A). Eight participants identified as women, six as men, one as gender-fluid, and one preferred not to disclose. Their average age was 48.0 years (*SD*=15.4). Twelve participants used JAWS screen reader [19], two used NVDA [1], and two used VoiceOver [11]. Seven participants were blind since birth, whereas five had lost vision gradually, with nine participants having complete blindness. We compensated our participants with a $20 Amazon gift card for 45 minutes of their time and conducted our user interviews online using Zoom. Specifically, we explored the following:

(1) Are screen-reader users conceptually familiar with data uncertainty in visualizations?
(2) Did participating in the study help advance their knowledge of data uncertainty in visualizations?
(3) How do screen-reader users prefer the information on data uncertainty in visualizations conveyed to them?

2.2 Analysis

We used thematic analysis [3] to analyze our interviews. We followed a semantic approach (identifying themes within the explicit or surface meanings of the data) [16], guided by an essentialist paradigm (focusing on reporting the experiences of the participants) [17, 29]. We developed 12 initial codes, transforming them into eight axial codes. Our axial codes revealed two themes and one suggestion as answers to our research questions.

2.3 Results

We discuss the two themes and one suggestion that emerged as findings from our semi-structured interviews.

2.3.1 Unfamiliarity with Uncertainty in Data Visualizations. Our findings showed that the participants lacked understanding of or were unfamiliar with uncertainty in data visualizations. Therefore, during the interviews, we explained the meaning of "uncertainty in data visualizations" using plain language and provided examples to familiarize them with the concept. After gaining familiarity, they expressed interest in learning more than the average values to draw more informed conclusions from the data. For example, P4 said, "*Now that I understand the term, I think it can be very handy actually.*"

To further analyze the perceived importance of uncertainty in data visualizations, we collected our participants' subjective ratings using a 1- to 7-point Likert scale before and after the interviews. 1 represented "not important at all" and 7 was "extremely important." The median of the participants' perceived importance before and after partaking in the study was 4.0 (*IQR*=3.3) and 5.5 (*IQR*=1.3), respectively. This difference was statistically significant based on Wilcoxon signed-rank test (Z=3.47, p<.001) [28], highlighting the significance of introducing users to the meaning and benefits of uncertainty in data visualizations.

2.3.2 Summary First, Details Later. Our participants shared their preference for exploring the data holistically first and then in a drilled-down manner, validating the findings from prior work [20, 24]. Specifically, our participants suggested a twofold solution. For example, P16 advised noting in the summary (or "alt-text") that users should cautiously interpret the data when high variation exists in the aggregated means and then provide opportunities for users to dig deeper into the data: "*Let's say the description says, this is the chart about, and this is the axis, these are the ranges, stuff like that. But also, use this data with caution because this data might not be representative of the population. And um, and then further, people are given the opportunity to, kind of, dig deeper and actually see all of those data points if they wanna.*"

To delve deeper into the data, our participants suggested using measures including tabular representation of the entire dataset and textual details using the "longdesc" attribute. For example, P11 expressed their opinions on using a data table: "*I'd use a table, a simple standard table with rows and cells and put the values in rows and columns. And then try to find any data points and then manually go through them to pull out what I need.*" Similarly, P2 shared a possible solution involving the "longdesc" attribute: "*Longdesc will bring up a page for that only, usually only screen readers can grab. It's like, the chart is actually a link to a description, which would describe all that stuff, like uncertainty and stuff.*"

To convey data uncertainty, our participants showed interest in knowing statistical information, including the margin of errors and confidence interval for each aggregated data point. For example, P1 expressed the benefit of such information for accurately understanding polling data: "*I'm really big into the election season. So many times, you know, margin of errors, confidence level, you know, will help me in trying to understand the pool numbers and see how accurate are they.*"

2.3.3 Keep Statistical Jargon for the Experts. Our participants articulated the need to adapt the information on data uncertainty presented to the users based on their expertise and comfort level with statistical terms and jargon. For example, P12 recommended using plain language and common words for easier understanding and an option to get specific statistical information for expert users: "*I guess a lot of it depends on the sophistication of your user. You know, if they have a sophisticated understanding of statistics, they might wanna really know what is the error bar value or what is the confidence interval or they might really need that level of specificity. If it's a layperson, um, then you might just be able to say, you know, use this with caution, or something like that.*"

We utilized these findings to enhance the functionalities of VoxLens, which we discuss in the section below.

3 VOXLENS ENHANCEMENTS

We extended the capabilities of the open-source VoxLens library [23] by utilizing the findings from our interviews. We present the details of our enhancements.

3.1 Overview of VoxLens

VoxLens is an open-source JavaScript plug-in that improves the accessibility of online data visualizations for screen-reader users using a multi-modal approach [23]. VoxLens offers two modes for holistic exploration of data (*Summary* and *Sonification*) and one mode for drilled-down exploration (*Question-and-Answer*). VoxLens does not currently convey information on data uncertainty in online visualizations. Therefore, in this exploration, we enhanced VoxLens to relay this information through its *Question-and-Answer* mode.

3.2 Determining and Conveying Uncertainty

To determine and convey uncertainty in online visualizations, we calculate the 50^{th} percentile (median) of the coefficient of variation (CV) value, which is the ratio between the standard deviation (provided by the visualization creator) and the dependent variable value (mean). Motivated by the suggestions from our participants in the interviews, we recommend users cautiously interpret the data for values higher than the median. Additionally, we relay the minimum and maximum values if provided by the visualization creators.

For example, without the enhancements, if the user asks for the data for *Jake* when interacting with the visualization using VoxLens' *Question-and-Answer* mode, the response from VoxLens would be: "*The value for Jake is [average].*" With our enhancements, it was: "*The average value for Jake is [average]. The minimum score for Jake was [minimum]. The maximum score for Jake was [maximum]. Use the data with caution. Data has higher variation than 50% of other names and may not be reliable*" (see Figure 1). Following the suggestion from our interview results, we avoided using statistical jargon in the responses from our enhancement.

3.3 Code Integration

Visualization creators use a traditional JSON file to generate data visualizations using VoxLens, specifying the independent and dependent variable values. Since this information is insufficient to compute CV, we added the functionality for visualization creators to provide more details about each data point. Specifically, they can supply the minimum, maximum, and standard deviation and specify if the dependent variable values represent an average. Appendix B shows a "before" and "after" code integration example.

4 DISCUSSION

In this preliminary exploration, we conducted semi-structured interviews with 16 screen-reader users to understand their preferences in obtaining information about uncertainty in data visualizations. Our findings showed that participants were initially unfamiliar with data uncertainty. After gaining familiarity, they suggested a hybrid solution to convey this information using plain language for novice and statistical terms for expert users. We utilized our findings to enhance VoxLens, an open-source tool that makes online data visualizations accessible to screen-reader users.

Prior work has shed light on the significance of providing information on data uncertainty in visualizations, as visualizations portraying only the "means" may be misleading and potentially dangerous [2, 4, 7, 10, 25]. Although our work focuses on conveying this information to screen-reader users, our findings show that our participants were initially unfamiliar with data uncertainty. This finding accentuates the importance of providing users with awareness of the subject matter to interpret data from visualizations accurately. While our enhancements to VoxLens enable visualization creators to supply additional information about data, we encourage future work to investigate ways to improve the understanding of users on data uncertainty, including users who use screen readers.

We enhanced the functionalities of VoxLens to convey information on data uncertainty to screen-reader users by incorporating the results from our study. However, it is noteworthy that our generalizable findings from our semi-structured interviews provide recommendations for visualization creators to supply this information for online data visualizations even where VoxLens may not be usable (e.g., image-based visualizations). For example, visualization creators can conjunctively use "alt-text" and "longdesc" attributes to support novice and expert users both. Altogether, we hope our work will open doors to new conversations and opportunities for future research, highlighting the importance of including non-visual users in inherently visual solutions.

4.1 Limitations & Future Work

In this exploratory work, we extended the capabilities of VoxLens using the findings from our interviews with screen-reader users. We aspire to conduct longitudinal user studies to evaluate the performance of our enhancements to VoxLens and iteratively improve them following a user-centered design protocol, which will also reduce any potential novelty effect. We note that our approach to convey uncertainty information using the 50th percentile) does not cover all edge cases (for example, when CV values are too close to each other or when all CV values are within the acceptable range). Future work can also investigate conveying information about uncertainty (e.g., error bars) in tools other than VoxLens.

ACKNOWLEDGMENTS

This work was funded by the University of Washington Center for Research and Education on Accessible Technology and Experiences (CREATE). We thank Jeffrey Heer and Jacob Wobbrock for their insightful advice, suggestions, and feedback. Finally, we thank our passive team members, Harry and Gemma, for their feline support and keystrokes on this manuscript (subsequently erased by the authors upon mutual consensus).

REFERENCES

[1] NV Access. n.d.. NV Access | Download. https://www.nvaccess.org/download/. (Accessed on 08/08/2021).

[2] Gennady Andrienko, Natalia Andrienko, Steven Drucker, Jean Daniel Fekete, Danyel Fisher, Stavros Idreos, Tim Kraska, Guoliang Li, Kwan Liu Ma, Jock D. Mackinlay, et al. 2020. Big data visualization and analytics: Future research challenges and emerging applications. , 8 pages. http://urn.fi/URN:NBN:fi:aalto-202103222554

[3] Virginia Braun and Victoria Clarke. 2006. Using thematic analysis in psychology. *Qualitative research in psychology* 3, 2 (2006), 77–101.

[4] Ken Brodlie, Rodolfo Allendes Osorio, and Adriano Lopes. 2012. A review of uncertainty in data visualization. In *Expanding the frontiers of visual analytics and visualization*. Springer, New York, USA, 81–109.

[5] Jinho Choi, Sanghun Jung, Deok Gun Park, Jaegul Choo, and Niklas Elmqvist. 2019. Visualizing for the non-visual: Enabling the visually impaired to use visualization. *Computer Graphics Forum* 38, 3 (2019), 249–260.

[6] Google Developers. 2014. Charts. https://developers.google.com/chart/

[7] Evanthia Dimara, Harry Zhang, Melanie Tory, and Steven Franconeri. 2022. The Unmet Data Visualization Needs of Decision Makers Within Organizations. *IEEE Transactions on Visualization and Computer Graphics* 28, 12 (2022), 4101–4112. https://doi.org/10.1109/TVCG.2021.3074023

[8] Danyang Fan, Alexa Fay Siu, Hrishikesh Rao, Gene Sung-Ho Kim, Xavier Vazquez, Lucy Greco, Sile O'Modhrain, and Sean Follmer. 2023. The Accessibility of Data Visualizations on the Web for Screen Reader Users: Practices and Experiences During COVID-19. *ACM Transactions on Accessible Computing* 16, 1 (2023), 1–29.

[9] Danyang Fan, Alexa Fay Siu, Wing-Sum Adrienne Law, Raymond Ruihong Zhen, Sile O'Modhrain, and Sean Follmer. 2022. Slide-Tone and Tilt-Tone: 1-DOF Haptic Techniques for Conveying Shape Characteristics of Graphs to Blind Users. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 477, 19 pages. https://doi.org/10.1145/3491102.3517790

[10] Jessica Hullman. 2019. Why authors don't visualize uncertainty. *IEEE transactions on visualization and computer graphics* 26, 1 (2019), 130–139.

[11] Apple Inc. n.d.. Accessibility - Vision - Apple. https://www.apple.com/accessibility/vision/.

[12] Chris Johnson. 2004. Top scientific visualization research problems. *IEEE Computer Graphics and Applications* 24, 4 (2004), 13–17.

[13] Aasim Kamal, Parashar Dhakal, Ahmad Y Javaid, Vijay K Devabhaktuni, Devinder Kaur, Jack Zaientz, and Robert Marinier. 2021. Recent advances and challenges in uncertainty visualization: a survey. *Journal of Visualization* 24, 5 (2021), 861–890.

[14] Edward Kim, Connor Onweller, and Kathleen F McCoy. 2021. Information Graphic Summarization using a Collection of Multimodal Deep Neural Networks. In *2020 25th International Conference on Pattern Recognition (ICPR)*. IEEE, Institute of Electrical and Electronics Engineers, New York, NY, USA, 10188–10195.

[15] Silvia Mirri, Silvio Peroni, Paola Salomoni, Fabio Vitali, and Vincenzo Rubano. 2017. Towards accessible graphs in HTML-based scientific articles. In *2017 14th IEEE Annual Consumer Communications Networking Conference (CCNC)*. IEEE, Las Vegas, NV, USA, 1067–1072. https://doi.org/10.1109/CCNC.2017.7983287

[16] Michael Quinn Patton. 1990. *Qualitative evaluation and research methods*. SAGE Publications, Inc., Thousand Oaks, CA, USA.

[17] Jonathan Potter and Margaret Wetherell. 1987. *Discourse and social psychology: Beyond attitudes and behaviour.* Sage, London, England.

[18] Jibonananda Sanyal, Song Zhang, Gargi Bhattacharya, Phil Amburn, and Robert Moorhead. 2009. A user study to compare four uncertainty visualization methods for 1d and 2d datasets. *IEEE transactions on visualization and computer graphics* 15, 6 (2009), 1209–1218.

[19] Freedom Scientific. n.d.. JAWS® – Freedom Scientific. https://www.freedomscientific.com/products/software/jaws/. (Accessed on 08/08/2021).

[20] Ather Sharif, Sanjana Shivani Chintalapati, Jacob O. Wobbrock, and Katharina Reinecke. 2021. Understanding Screen-Reader Users' Experiences with Online Data Visualizations. In *The 23rd International ACM SIGACCESS Conference on Computers and Accessibility* (Virtual Event, USA) *(ASSETS '21)*. Association for Computing Machinery, New York, NY, USA, Article 14, 16 pages. https://doi.org/10.1145/3441852.3471202

[21] Ather Sharif and Babak Forouraghi. 2018. evoGraphs — A jQuery plugin to create web accessible graphs. In *2018 15th IEEE Annual Consumer Communications Networking Conference (CCNC)*. IEEE, Las Vegas, NV, USA, 1–4. https://doi.org/10.1109/CCNC.2018.8319239

[22] Ather Sharif, Olivia H. Wang, and Alida T. Muongchan. 2022. "What Makes Sonification User-Friendly?" Exploring Usability and User-Friendliness of Sonified Responses. In *Proceedings of the 24th International ACM SIGACCESS Conference on Computers and Accessibility* (Athens, Greece) *(ASSETS '22)*. Association for Computing Machinery, New York, NY, USA, Article 45, 5 pages. https://doi.org/10.1145/3517428.3550360

[23] Ather Sharif, Olivia H. Wang, Alida T. Muongchan, Katharina Reinecke, and Jacob O. Wobbrock. 2022. VoxLens: Making Online Data Visualizations Accessible with an Interactive JavaScript Plug-In. In *CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 478, 19 pages. https://doi.org/10.1145/3491102.3517431

[24] Ather Sharif, Andrew M. Zhang, Katharina Reinecke, and Jacob O. Wobbrock. 2023. Understanding and Improving Drilled-Down Information Extraction from Online Data Visualizations for Screen-Reader Users. In *Proceedings of the 20th International Web for All Conference* (Austin, TX, USA) *(W4A '23)*. Association for Computing Machinery, New York, NY, USA, 18–31. https://doi.org/10.1145/3587281.3587284

[25] Ben Shneiderman, Catherine Plaisant, and Bradford W Hesse. 2013. Improving healthcare with interactive visualization. *Computer* 46, 5 (2013), 58–66.

[26] Alexa Siu, Gene S-H Kim, Sile O'Modhrain, and Sean Follmer. 2022. Supporting Accessible Data Visualization Through Audio Data Narratives. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 476, 19 pages. https://doi.org/10.1145/3491102.3517678

[27] Daniel Weiskopf. 2022. Uncertainty visualization: Concepts, methods, and applications in biological data visualization. *Frontiers in Bioinformatics* 2 (2022), 10.

[28] Frank Wilcoxon. 1945. Individual Comparisons by Ranking Methods. *Biometrics Bulletin* 1, 6 (1945), 80–83. http://www.jstor.org/stable/3001968

[29] Robin Wooffitt and Sue Widdicombe. 1995. *The language of youth subcultures: social identity in action.* Harvester Wheatsheaf, Birmingham, UK.

A STUDY PARTICIPANTS

Table 1: Screen-reader participants, their gender identification, age, screen reader, vision-loss level, and diagnosis. Under the *Gender* column, M = *Man*, W = *Woman*, GF = *Gender-Fluid* and "-" represents that the participant chose not to disclose their identity.

	Gender	Age	Screen Reader	Vision-Loss Level	Diagnosis
P1	M	43	JAWS	Blind since birth	Microphthalmia
P2	M	59	JAWS	Lost vision gradually	Cataracts and Glaucoma
P3	W	53	JAWS	Blind since birth	Retinopathy
P4	M	37	JAWS	Blind since birth	Leber Congenital Amaurosis
P5	M	55	JAWS	Blind since birth	Leber Congenital Amaurosis
P6	W	50	JAWS	Lost vision gradually	Retinitis Pigmentosa
P7	W	36	JAWS	Blind since birth	Retinopathy of Prematurity
P8	GF	28	NVDA	Blind since birth	Leber Congenital Amaurosis
P9	W	40	NVDA	Lost vision gradually	Stargardt Disease
P10	-	57	VoiceOver	Lost vision gradually	Retinopathy of Prematurity
P11	M	32	JAWS	Lost vision gradually	Retinal detachment
P12	W	41	VoiceOver	Lost vision gradually	Functional Neurological Disorder
P13	M	76	JAWS	Lost vision gradually	Retinitis Pigmentosa
P14	W	24	JAWS	Blind since birth	Astrocytoma
P15	W	65	JAWS	Lost vision gradually	Retinitis Pigmentosa
P16	W	72	JAWS	Lost vision gradually	Retinitis Pigmentosa

B "BEFORE" AND "AFTER" INTEGRATION CODE

Before

```
[
  {
    "name": "Alex",
    "score": 79
  }
  ...
]
```

After

```
[
  {
    "name": "Alex",
    "score": 79,
    "vx_metadata": {
      "min": 56,
      "max": 89,
      "stdev": 13.11,
      "isAverage": true
    }
  }
  ...
]
```

Figure 2: Integration code sample comparing original VoxLens to our enhanced version.