SMART ACCESSIBILITY 2025

The Tenth International Conference on Universal Accessibility in the Internet of Things and Smart Environments

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SMART ACCESSIBILITY 2025 Editors

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SMART ACCESSIBILITY 2025

Forward

The Tenth International Conference on Universal Accessibility in the Internet of Things and Smart Environments (SMART ACCESSIBILITY 2025) was held between May 18th, 2025, and May 22nd, 2025, in Nice, France.

There are several similar definitions for universal accessibility, such as design for all, universal design, inclusive design, accessible design, and barrier free design. These and similar approaches are relevant to this conference. The focus will be on methods, tools, techniques and applications for human diversity, social inclusion, and equality, enabling all people to have equal opportunities and to participate in the information society.

The accepted papers covered topics such as accessibility by design, digital inclusion, accessibility devices, and applications. We believe that the SMART ACCESIBILITY 2025 contributions offered a large panel of solutions to key problems in areas of accessibility.

We take here the opportunity to warmly thank all the members of the SMART ACCESSIBILITY 2025 technical program committee, as well as all the reviewers. The creation of such a high-quality conference program would not have been possible without their involvement. We also kindly thank all the authors who dedicated much of their time and effort to contribute to SMART ACCESSIBILITY 2025. We truly believe that, thanks to all these efforts, the final conference program consisted of top-quality contributions. We also thank the members of the SMART ACCESSIBILITY 2025 organizing committee for their help in handling the logistics of this event.

We hope that SMART ACCESSIBILITY 2025 was a successful international forum for the exchange of ideas and results between academia and industry for the promotion of progress on universal accessibility.

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Accessible Representations of Visual Artifacts in Technical Informatics Education

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***Abstract*—Graphical representations and diagrams are widely used in engineering disciplines. In computer science and electrical engineering, Unified Modeling Language (UML) diagrams, electronic circuit schematics, and Karnaugh-Veitch (KV) diagrams are commonplace. At our university, they are taught in courses of Technical Informatics and Software Engineering. However, these visual methods pose considerable barriers for students with visual impairments. Hence, using graphical representations is limiting educational accessibility and inclusivity. In response, this paper presents text-based alternatives which we have been using since three semesters to provide equivalent conceptual information in non-visual ways.**

Keywords-Accessibility; Visual Impairment; Inclusive STEM Education; UML Class Diagrams; Electronic Circuits Simulation; Logic Gate Modeling; Textual Representations; Educational Technology; Screen Reader Compatibility.

I. INTRODUCTION

Visual representations, including Unified Modeling Language (UML) diagrams, electronic circuit schematics, logic gates, and Karnaugh-Veitch (KV) diagrams, constitute foundational elements in technical informatics and software engineering education. These tools are employed universally to convey complex abstract and concrete concepts efficiently. Despite their educational value, these graphical representations pose significant accessibility challenges, rendering them unsuitable for blind and visually impaired students. Consequently, there is a pressing imperative to develop and implement effective alternatives to ensure equitable access to technical education, in line with international frameworks, such as the United Nations Convention on the Rights of Persons with Disabilities (UN-CRPD).

Graphical diagrams inherently rely on visual-spatial reasoning, which is inaccessible without visual perception or assistive adaptations. For visually impaired learners, these diagrams represent barriers that limit participation, understanding, and ultimately educational achievement in technical disciplines. This exclusion not only hinders individual educational outcomes but also contravenes principles of inclusivity and equal opportunity embedded in modern educational policies.

The motivation behind the present study emerged from practical challenges encountered at the University of Applied Sciences Mittelhessen (Technische Hochschule Mittelhessen: THM), where visually impaired students enrolled in technical informatics courses. Their participation highlighted an urgent need to adapt existing pedagogical materials to accessible formats. Hence, we initiated a focused research and development effort to address these challenges systematically.

Specifically, this paper addresses the following research questions: How can standard graphical representations in technical informatics be effectively translated into accessible text-based formats? What approaches ensure semantic equivalence and pedagogical effectiveness for both visually impaired and sighted students? Our primary objectives are to develop robust, text-based alternatives to conventional diagrams and evaluate their educational viability and inclusivity through empirical validation.

The remainder of this paper is structured as follows: Section II provides a critical review of existing approaches to accessible diagram representation. Section III presents our developed text-based solutions, detailing their conceptualization, implementation, and deployment. In Section IV, we describe our evaluation methodology and present the findings from structured interviews with visually impaired students. Finally, Section V discusses implications, limitations, and avenues for future research, concluding with a summary of our contributions.

The motivation for developing the solutions presented here stemmed from the enrollment of blind students in computer science at THM. This posed the challenge of how graphical representations, such as UML class diagrams, electronic circuit diagrams, and logic circuits could be supplemented or replaced by purely textual representations.

II. RELATED WORK

Ensuring accessibility of visual diagrams in STEM education has increasingly gained attention due to the imperative of providing equal learning opportunities for visually impaired students.

In the following subsections, we analyze major existing approaches, evaluating their potential and limitations in relation to our work.

A. Multimodal and Universal Design Approaches

Multimodal systems employing vibro-audio interfaces offer visually impaired students alternative interaction methods with visual content. Doore et al. [1] demonstrated that these systems effectively support both visually impaired and sighted students, underscoring the merits of universal design in educational environments. However, such solutions often require specialized hardware and considerable developmental effort, potentially limiting their scalability within typical educational settings.

B. Text-based Approaches for UML and Circuits

Text-based alternatives provide a pragmatic, cost-effective solution. Wildhaber et al. [2] proposed a method enabling visually impaired students to independently create and edit UML diagrams using accessible mobile interfaces. Their approach lowers the entry barrier compared to conventional textual UML tools like PlantUML and YAML. This work aligns with our experiences, confirming that textual representations not only mitigate accessibility barriers but also offer pedagogical benefits by emphasizing semantic structuring over visual complexity.

C. Tactile and Haptic Representations

Tactile approaches, such as the thermo-formed paper method proposed by Pissaloux et al. [3] for representing complex diagrams, facilitate haptic access to visual information. While these solutions are valuable, their creation and distribution are costly and logistically complex. Additionally, they lack flexibility and real-time adaptability, posing disadvantages in dynamic teaching contexts.

D. Interactive and Tangible Representations

Studies by Ducasse et al. [4][5] on interactive and tangible maps have highlighted the benefits of physical and digital interaction for spatial understanding among visually impaired individuals. Although their focus was on geographic content, the underlying principles of interactivity and tactile feedback could potentially transfer to other visual domains like electronic circuits. Yet, these approaches similarly demand specialized technology and significant spatial resources.

E. Synthesis and Connection to Our Work

The reviewed works illustrate diverse strategies for improving visual diagram accessibility. While multimodal and haptic methods constitute valuable additions, their inherent limitations include substantial resource demands and scalability issues. In contrast, text-based approaches such as PlantUML and YAML descriptions provide feasible, scalable alternatives. Our work builds directly upon these textual solutions, further developing them to offer semantically equivalent, pedagogically sound, and accessible alternatives for visual diagrams in technical informatics education. Thus, we address existing gaps and foster inclusive learning environments that effectively support both visually impaired and sighted students.

III. Methodological Approach

This study follows an exploratory case study design aimed at developing and evaluating text-based alternatives for graphical representations in technical informatics education. The research was conducted over three semesters at [the University], where blind and visually impaired students were enrolled in core technical courses.

The methodological approach consisted of a continuous design and implementation cycle, including the development of accessible teaching materials (e.g., text-based Karnaugh-Veitch diagrams, UML class diagrams using PlantUML, Java-based logic gate models, and LTSpice NetLists). These materials were integrated into regular courses, and their usability was evaluated through iterative feedback.

Feedback was collected from two blind students, referred to as Student A and Student B, using structured interviews. Their insights helped assess the comprehensibility, practicality, and educational effectiveness of the proposed solutions. The student testimonials included in this paper were originally provided in German and were translated into English for inclusion.

The philosophical stance guiding this work can be described as pragmatic, focusing on solving concrete accessibility challenges in the educational context and prioritizing practical outcomes over theoretical generalizations.

IV. Proposed Solutions

The following subsections present our solutions for making diagrams and electronic circuits accessible to visually impaired people.

A. Accessibility to Diagrams for Visually Impaired Individuals

The primary objective was to develop and employ textual representations as an alternative to graphical representations for sighted students, ensuring accessibility and inclusivity.

We set the following requirements:

- Purely textual representations.
- Concise communication of the concepts conveyed by graphical representations.
- Usability of textual representations by both sighted and visually impaired students.
- Seamless content exchange between sighted and visually impaired students during lectures.
- Use of design and simulation tools that support textual model descriptions.

The proposed solutions were developed iteratively over the past two years and tested in lectures. Collaboration with blind students and the Study Center for Blind and Disabled Students (BliZ) ensured their relevance and effectiveness. The different approaches for each type of graphical representation are introduced in the following Subsections.

1) Karnaugh-Veitch Diagrams (KV Diagrams): KV diagrams simplify Boolean functions and minimize digital logic circuits. They were encoded as Markdown tables.

As an example, the truth table for a Logic NAND Gate which is a combination of a digital logic AND gate and a NOT gate connected together in series.

```
| Nr | B | A | Y |
|----|---|---|---|
| 0  | 0 | 0 | 1 |
| 1  | 0 | 1 | 1 |
| 2  | 1 | 0 | 1 |
| 3  | 1 | 1 | 0 |
```

A KV Diagram for the NAND:

```
|  Y | !A | A  |
|----|----|----|
| !B | 1  | 1  |
| B  | 1  | 0  |
```

The Boolean expression of the NAND operation is:

$$Y = A \text{ NAND } B = \overline{A \land B}$$

In addition to the actual logical operation, the LaTeXcode of this formula includes additional rendering information. This affects the readability for blind people.

```
\[
Y = A \text{ NAND } B = \overline{A \land B}
\]
```

We used a simplified text version for Boolean expressions:
Y = A NAND B = !(A*B)
This simplified form is particularly barrier-free.

2) UML Class Diagrams: In the lectures *Programming* and *Technical Informatics*, UML class diagrams are introduced to visualize the structure of individual classes (name, attributes, methods, visibility) and relationships between classes.

To make these concepts independent of graphical representations, structural elements, such as attributes, methods, and class relationships (e.g., aggregation, composition, inheritance), were emphasized in textual form.

In a search, the following open source tools were found that enable barrier-free access to UML diagrams:

- *UML4ALL* (https://www.uml4all.net)
- *PlantUML* (https://plantuml.com)

Both tools were evaluated. *PlantUML* was chosen for its simplicity and browser-based functionality. *PlantUML* specifies a textual description of classes and provides a rendering tool which generates class diagrams from the textual description.

Here is an example of the textual description and the resulting diagram (Figure 1).

```
@startuml
class Person{
+ firstname. String
+ name: String
}
class Student {
+ matrNr: int
}
Person ^-- Student

class Lecturer {
+ departmentmatrNr: String
}
Person ^-- Lecturer

class Course {
+ title: String
+ lecturer: Lecturer
}
Course o-- Lecturer
@enduml
```

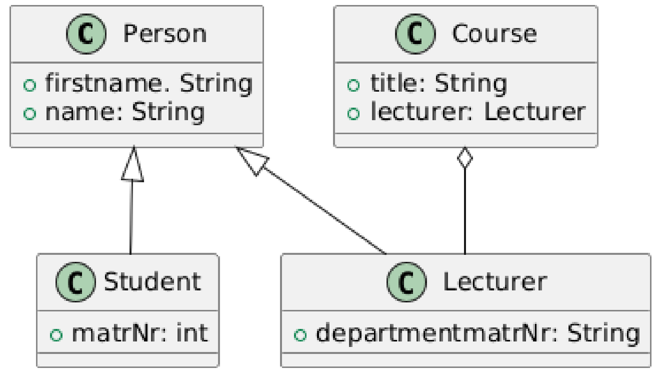

Figure 1. Generated class Diagram.

Class diagrams were presented in textual form in lecture materials, exercises, and exams, ensuring consistency between textual and graphical formats.

3) Logic Gates: Several tools are available for drawing and simulation of logic gates and circuits.

We use the Web-based tool *Circuit.js* for the development and simulation of circuits. Figure 2 shows a logic circuit of a full adder.

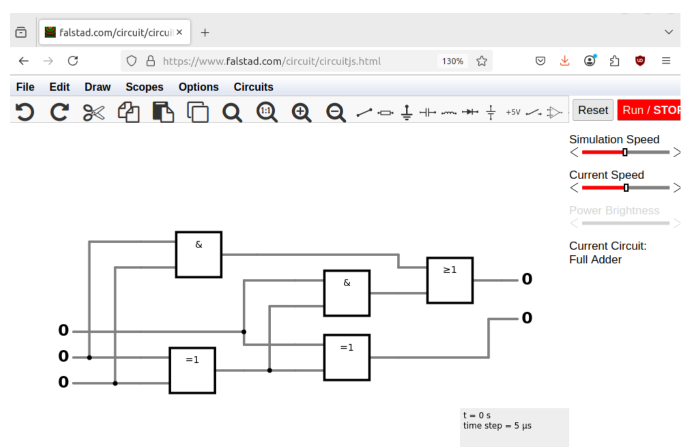

Figure 2. Circuit of a Full Adder.

Because this simulation tool works purely graphically, it is not barrier-free.

Textual specifications of logic gates and circuits are done by using Hardware Description Languages (HDL), like *Very High Speed Integrated Circuit Hardware Description Language* (VHDL).

However, introducing HDL in the first semester alongside Java was deemed pedagogically inappropriate. Instead, logic gates were implemented as Java classes.

As an example, this listing shows the code for an AND gate:

```
class AndGate {

    private boolean x1;
    private boolean x2;
    private boolean y;

    public void setX1(boolean x1)
        { this.x1 = x1; }

    public void setX2(boolean x2)
        { this.x2 = x2; }

    public boolean calculate() {
        y = x1 && x2;
        return y;
    }
}
```

Students built circuits as interacting objects and validated their behavior by printing out truth tables in the main() method.

B. Development and Simulation of Electronic Circuits for Visually Impaired Individuals

1) Motivation and Accessibility Challenges: Traditional graphical circuit schematics pose significant challenges for visually impaired students, as they rely heavily on visual elements that are difficult to interpret without specialized assistive technologies.

While previous sections have demonstrated how digital logic circuits can be implemented and simulated using Java, this approach does not address analog circuits. To fill this gap and enhance conceptual understanding for blind students, LTSpice is introduced as an accessible tool.

LTSpice, a widely used circuit simulation tool, presents additional obstacles due to its graphical interface, which is not optimized for screen readers or other accessibility tools [6]. To overcome these limitations, a text-based alternative is required, allowing visually impaired students to design and simulate electronic circuits effectively using structured NetLists instead of graphical schematics. An alternative option, Verilog-A (Verilog Analog), was considered; however, its complexity makes it unsuitable for first- and second-semester students.

This approach ensures inclusivity by enabling all students to participate in circuit analysis and development using accessible tools, while maintaining an appropriate level of complexity for introductory courses. Figure 3 shows a screenshot of a simple analog-circuit in LTSpice and its simulation-output in the waveform viewer.

2) NetList-Based Circuit Design: The NetList format provides a structured, text-based alternative to traditional graphical schematics, allowing visually impaired students to design and simulate electronic circuits efficiently. Unlike graphical editors, which require users to manually position and connect components, NetLists define circuits using a standardized

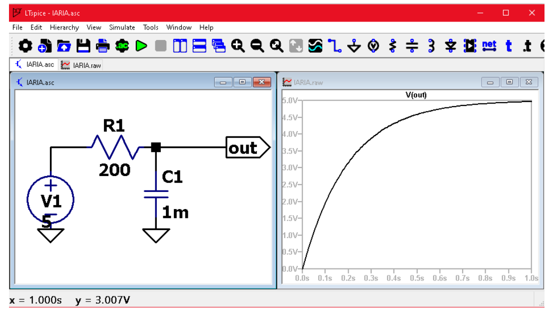

Figure 3. Example of an LTSpice Circuit Schematic.

syntax that can be easily interpreted by screen readers and assistive technologies.

A NetList consists of:

- **Component Definitions**: Each electrical component, such as resistors, capacitors, and voltage sources, is explicitly declared along with its respective parameters.
- **Node Connections**: Components are connected using numerical node identifiers, forming a network that describes the electrical relationships between circuit elements.
- **Simulation Directives**: Commands that instruct LTSpice on how to process the circuit, such as transient analysis settings.

Below is the circuit shown in Figure 3 in its simple NetList (.net) representation:

```
* voltage source (5) to Ua and ground (0)
V1 Ua 0 5
* Resistor (200 Ohms)
* from node Ua to node out
R1 Ua out 200
* Capacitor (1mF) to node out and ground (0)
C1 out 0 1m
* Simulate for 1 Second
.tran 1
```

This format ensures accessibility by allowing circuits to be designed, edited, and simulated using simple text files, which can be read and modified with any text editor. The structured approach also enables integration with screen readers, making circuit design more inclusive for visually impaired students.

3) Simulation in LTSpice using NetLists: LTSpice allows for the execution of circuit simulations using NetLists without relying on its graphical schematic editor, making it an accessible tool for visually impaired students. The simulation process can be carried out using command-line operations or script execution, ensuring a non-graphical workflow.

To import and simulate a NetList in LTSpice, follow these steps:

- Open the NetList file (.net) in a text editor and ensure its correctness.
- Load the NetList in LTSpice using the command-line interface.
- Execute the simulation using predefined analysis directives (e.g., `.tran` for transient analysis, `.ac` for frequency response).

Upon completion, LTSpice generates structured text-based simulation results. These outputs can be saved in CSV format or parsed into structured tables, allowing for further processing by screen readers or custom analysis tools for visually impaired users.

4) Alternative Output Formats for Accessibility: One of the major challenges for visually impaired students using LTSpice is the lack of accessibility in the waveform viewer. To address this, simulation results can be exported in text format, enabling alternative representations that are more accessible.

- Text Export via `.print` Commands:

  ```
  .print tran V(Ua) V(out)
  ```

  The output is stored as a CSV file, allowing further processing with text editors or screen readers.
- Structured Table Representation: Instead of visual graphs, data can be displayed in a structured tabular format:

Time (s)	V(Ua)	V(out)
0.0	5.00	0.00
1.0	5.00	3.25
2.0	5.00	4.75

- Alternative Representations for Accessibility:
  - *Auditory Representation*: Using screen readers to read out the values sequentially.
  - *Tactile Representation*: Converting CSV data into a Braille format for students using Braille displays.
  - *Speech Synthesis*: Generating spoken descriptions of circuit behavior based on data trends.

5) Comparison: NetList vs. Graphical Schematic Input: The use of NetLists as an alternative to graphical circuit schematics presents both advantages and challenges.

Advantages:

- Provides **full accessibility** for visually impaired students, as it eliminates the reliance on visual representations.
- Allows **easy editing** using text editors with screen reader support.
- Enables **collaboration** with sighted students, as NetLists can be converted into graphical schematics when necessary.

Challenges:

- Requires learning a **specific syntax**, which might be an initial hurdle for some students.
- Does not support **intuitive spatial representation** of circuit layouts, making it harder for sighted individuals accustomed to schematic views.

6) Future Improvements: Several enhancements can be developed to further improve accessibility in electronic circuit design and simulation:

- **Integration of automatic speech synthesis**: This would allow simulation results to be read aloud, enabling better analysis for visually impaired students.
- **Development of haptic feedback solutions**: Tactile output devices could be used to provide a physical representation of circuit behavior.
- **Implementation of a user-friendly interface**: Creating an optimized LTSpice interface tailored to the needs of visually impaired users could enhance usability and efficiency.
- **Conversion tools for bidirectional translation**: Software that converts NetLists into graphical schematics and vice versa would support collaboration between sighted and visually impaired students.

By implementing these improvements, LTSpice can become a more inclusive tool that ensures equal opportunities for all students in electronic circuit design and simulation.

V. Feedback from Students

We asked two blind students for a statement comprising their experiences with the described approaches.

Student A:

> Experiences with barrier-free access to course material - Computer Engineering I in summer term 2024
>
> As a visually impaired student at the university, I attended the module **Computer Engineering I** in the summer term 2024, which was offered by [the professor].
>
> I would like to share my experiences with barrier-free access to the course content.
>
> As for the lecture slides during the semester, [the professor] kindly provided them to me in Markdown format. In the lectures, we used the open-source project Etherpad, which proved to be a very suitable solution for sharing notes in the classroom.
>
> Another approach to teaching logic gates during the semester was to use LTSpice-Netlists to simulate circuits. We then implemented the gates as C++ classes, which contributed significantly to the deepening and better understanding of the material.
> Finally, we worked with an implementation of the Von Neumann Machine Simulator, which provided a good insight into the processes of programs at machine level.
> All tools and alternative solutions used were tested with NVDA under Windows and worked perfectly. With regard to platform independence, it should be mentioned that the LTSpice application does not run directly under Linux. However, there are command line alternatives that can be used as a replacement.

Student B:

> Although visual concepts such as class diagrams were sometimes taught in Object-Oriented Programming (OOP), the lecturer managed to make them clear to me using PlantUML.
>
> The Etherpad helped me a lot to follow the blackboard notes or presentation and to understand class diagrams.

Original text in German, here translated. Student names replaced by 'A' and 'B'.

VI. Conclusion and Future Work

In this paper, we have introduced and evaluated a suite of text-based representations designed to make graphical diagrams in technical informatics education accessible for blind and visually impaired students. Our proposed solutions include PlantUML for a textual specification of UML class diagrams, simplified netlists for electronic circuit schematics, Java-based models for logic circuits, and structured Markdown representations for Karnaugh-Veitch diagrams.

Empirical evaluation through structured interviews demonstrated that these text-based approaches are comprehensible, practical, and pedagogically effective, significantly enhancing accessibility and inclusivity in mixed-ability classrooms. The significance of these findings is manifold. Primarily, our work contributes towards reducing educational barriers, thus aligning with broader inclusivity mandates such as those outlined in the UN-CRPD.

The demonstrated efficacy of text-based solutions establishes a practical foundation for scalable and sustainable educational practices, making complex technical content universally accessible without relying heavily on costly, specialized technology. However, our approach is not without limitations. Text-based representations require initial familiarization with specific syntactic conventions, which can pose challenges to some students. Additionally, the loss of intuitive spatial layouts inherent in graphical schematics might complicate conceptual understanding, particularly for sighted students accustomed to visual aids.

Future work should focus on addressing these limitations and further enhancing the usability and effectiveness of text-based approaches. Possible research directions include the development of hybrid solutions integrating text-based methods with haptic or auditory feedback, thus combining accessibility with intuitive comprehension. Additionally, automated tools facilitating bidirectional conversion between textual representations and graphical diagrams could foster better collaboration between sighted and visually impaired students. By addressing these challenges, we can continue advancing towards genuinely inclusive technical informatics education, enabling equitable learning opportunities for all students.

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Digital Accessibility for Persons with Color-blindness

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***Abstract*— The present work highlights the perceptibility of digital content for people with color blindness. It presents a pragmatic requirements catalog for user interface programmers and developers, devising layouts and digital prototypes that are to incorporate a mode for color blindness. Criteria catalogs, such as Web Content Accessibility Guidelines 2.1 are used for determining the requirements. A tool is employed to analyze the contrast of digital contents. Based on the results and the criteria of WCAG 2.1, an actionable catalog of requirements is presented. This work enables the determination of aspects of particular relevance. The paper thus provides information on color blindness and visual impairments, as well as a guideline that provides interested developers with "best practices" to optimize web applications in terms of accessibility and to utilize as a guide.**

Keywords - Web Content; Digital Accessibility by Design; Color-blindness.

I. INTRODUCTION

A person with an unimpaired color perception can perceive and process countless colors of the spectrum. However, it is estimated that around 0.4% of all women and 8% of all men are impaired in their color perception and do not perceive colors in the same way as 95% of all other people do. One form of color blindness is total color blindness, i.e., purely monochromatic vision, in which the affected person only perceives black and white, i.e., only the differences in brightness of the different colors. If, on the other hand, the perception of only one of the three primary colors red, green and blue is impaired, which occurs in around 60% of color-blind people, the term dichromatic vision is used. These can generally be divided into the following groups, which are also simulated and presented in Figure 1. A distinction can be made between protanopes and deuteranopes, red-green-blinds "whereby protanopes require high-intensity long-wave radiation for recognition, and tritanopes, yellow-blue-blinds" [1]. Protanopes and deuteranopes confuse colors, such as red, yellow, brown and green, cannot tell the difference between violet and blue, and protanopes in particular only see dark red as black. Color-blind people who belong to the tritanopic group, on the other hand, have difficulty distinguishing blue from green and yellow-green from grey. People who do not suffer from any impairment of their color perception, on the other hand, are referred to as trichromats, i.e., "people without color vision deficiency and with normal spectral sensitivity" ([1]: 270), although they may also have anomalies that make them perceive colors slightly differently than the majority.

Figure 1. Overview of a demonstration of vision with the different types of color vision deficiency the full colour spectrum [2].

This article describes various forms of dysfunctional vision concerning colors. It will set out why it is important for content creators to implement digital accessibility for persons with color-blindness into their design processes. It lays forth why this kind of digital accessibility is not only a technical issue.

This research also discusses technical tools available for content optimization.

II. AUXILIARY TOOLS USED

There are many different approaches for analyzing the contrast ratios of foreground and background. The developer tools of common Internet browsers can already be used to determine the contrast ratio by examining an element of the surface. However, this does not work for every element that you want to examine, so it makes sense to use other tools that can make the work a little easier and provide even more information. For the intended purpose, however, these tools must be able to do more than just display the contrast ratio. In addition to recommendations and cross-references to interesting articles, the authors of the WCAG 2.1 guidelines also provide recommendations for tools to determine contrast ratios [3]. One of the recommendations is the product of Utah State University's WebAim.org [4], which offers a web- based tool for free download that is designed to analyze the contrast ratios between two different colors (see Figure 2).

The tool makes it possible to analyze the content and use the data to make it more accessible for people with a possible visual impairment. In addition to using indicators to indicate whether the calculated contrast ratio is

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compatible with WCAG requirements, the application offers users the option of simulating color blindness using a specific function and using a sample text to show how the respective contrast ratio is perceived by people with color vision impairments. The color values can be determined in several ways and can also be specified in the most common formats [2]. Users can also copy the results provided by the Color Contrast Checker and use them for other purposes. Even slight deviations of the text contrast from the maximum (black; see Figure 2) drastically reduce readability, as in the example of dark blue (see Figure 3).

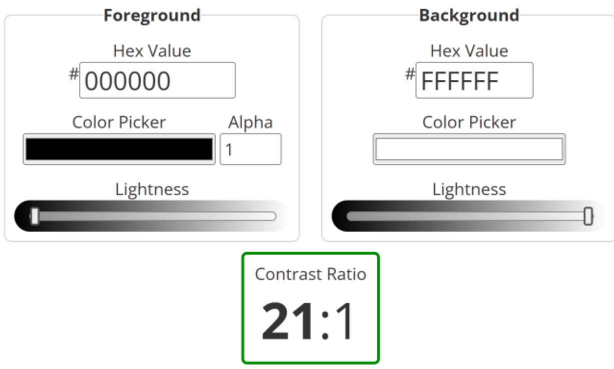

Figure 2. The user interface of the Color Contrast Checker [4] is shown here as an example.

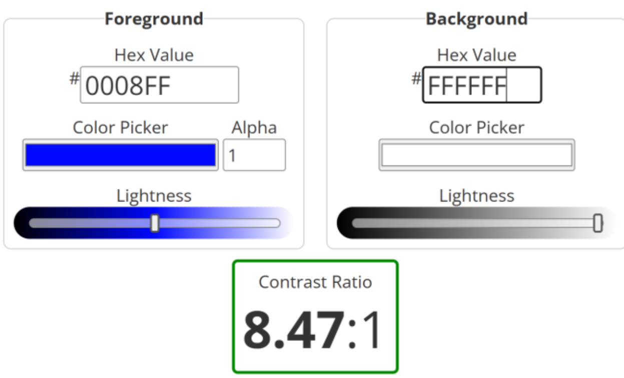

Figure 3. Reduction of contrast from 21:1 to 8,47:1 by replacing black writing with dark blue. Tool: Color Contrast Checker [4].

As demonstrated, this tool is used to examine and analyze the success criteria 1.4.3 "Contrast (Minimum)," 1.4. 6 "Contrast (Enhanced)," and 1.4.11 "Non-text Contrast“ of the WCAG [3] in more detail. The rest of the criteria can be carried out by examining the elements through the developer options of the browser employed.

III. CATALOG OF REQUIREMENTS

The basis is initially formed by the requirements from the WCAG guidelines [3], in particular from Guideline 1.4, which addresses the differentiability of content. The catalog designed is intended to sustainably improve the differentiability and perceptibility of texts, graphics, and user interfaces, thus optimizing those for users with color blindness/ color-related visual impairment. The requirements are also inspired by the related work of Ebert et al [5], whose analysis identified further requirements for web offerings.

A. Color

The most important feature of a color-blindness/ color-related visual impairment mode is the color factor. The success criterion for barrier-free use is that information is not conveyed exclusively via colors. This means that there are alternatives for conveying information, i.e., that color is not used exclusively as a transport medium. Options, such as the use of icons or the textual presentation of information are useful and should be considered. In addition, certain colors should be banned as a matter of principle or the use of colors, such as green, red or blue should be avoided within the digital content, as there are known color vision deficits [3], as in WCAG success criterion 1.4.1. In order to design, e.g., a successful prototype of an accessible web application, it is important to weigh up the benefits, aesthetics and purpose of the color scheme so that a meaningful overall design can be created. Text input via form fields in particular can become a challenge for those affected if an unsuccessful request is signaled exclusively via red color accents. This can lead to misunderstandings during operation, which users may perceive negatively and perhaps put them off completely. It is important not to make the different statuses of operating elements dependent on color and to consider alternatives. Labels that clearly and comprehensibly convey the required information and speak for themselves in their simplicity are suitable. An exclamation mark has roughly the same effect as the signal color red and can therefore convey just as strongly that certain inputs are necessary. It has however to be stated that some visually impaired users feel more comfortable when higher contrasts with colors are used instead of classic black and white ([3]: 85).

B. Font

In addition to the color of content, font size is also a decisive factor that significantly influences the legibility of content and, above all, text. This not only brings exclusive advantages for people with a visual impairment, but also makes content clearer and facilitates the identification of the functionality of the constituents of a website. As control elements are essential for the use of interactive platforms, it is important to design them clearly and legibly so that users can use the application as desired. The text size of elements should therefore not be less than 18.5px, as this can impair the quality of differentiability ([3], success criteria 1.4.3 & 1.4.6). If buttons or information-laden texts cannot be read, this unsettles users in their actions and can also have a deterrent effect. An overview and good legibility promote perceptibility and increase the differentiability of the content. Texts should be prepared in such a way that, if they are enlarged, they are still legible and the formatting does not suffer or deteriorate. All inscriptions should meet this

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criterion, especially if users use supplementary assistive technologies. All of this contributes to the acceptability of a solution in that people with visual impairments can follow the text better and that it is generally clearer to read ([3], success criterion 1.4.4).

C. Contrast

In addition to the two previous factors, contrast is also of significant importance for differentiable content on user interfaces. For example, white text that meets all the criteria for legible text can hardly be perceived on a light gray background, simply because the contrast ratio is so low that the foreground can hardly be differentiated from the background. Poor contrast leaves control elements almost unusable and therefore also makes the platform unsuitable for efficient work. Particularly, in user interfaces that consist of countless control elements, it is essential that these are labeled and marked according to their function. If there is an insufficient contrast ratio between the foreground and background, the labeling can no longer be perceived and users can no longer understand what function the control element has ([3], success criteria 1.4.3 & 1.4.6 & 1.4.11). This implies that a good contrast ratio is essential for the interface and its controls. In the least, a standard value of 7.5:1 for normal text and labeling within images should be adhered to so that its content is optimally perceptible. Text with a large font size, on the other hand, only needs a contrast ratio of at least 4.5:1 to meet the requirements ([3], success criteria 1.4.3 & 1.4.6).

A current example is the logo of Merck KGaA in Figure 4.

Figure 4. Corporate logo of Merck KGaA [7]

Even though the font is large, the contrast ratio of 2,27:1 does not suffice for adequate readability. The reception of pictures can be simulated on Dalton Lens Website [8].

According to Brettel [9] et al., the result for red-blind readers (with so-called protanopia) would look like in Figure 5.

Figure 5. Simulation of Merck KGaA logo on Dalton Lens Website [8] using the Brettel method [9].

One of the additional findings of the analysis carried out at is that light/dark contrasts in particular improve the contrast ratio enormously. The use of a complementary contrast between red and green, on the other hand, is an absolutely avoidable scenario that should never find its way into a user interface.

D. Scalability

Another requirement to consider is the scalability of content. This means that the surface can be enlarged to up to at least 200% of the actual display size. On the one hand, this helps people with weaker eyesight to enlarge the content so that they can better perceive and differentiate it. On the other hand, this requirement makes it possible for users with devices that have a lower pixel density or smaller screens, for example, to enlarge the content. Above all, this ensures ergonomic advantages, as content is not only perceptible for all users, but can also be accessed regardless of the device. It is important that content retains its full functionality and is legible even with a larger zoom factor (see [3], success criteria 1.4.8 & 1.4.10). The results of the analysis of the collected data and the expert opinions [3] also confirm the assumption that it is desirable for users if user interfaces offer the possibility to adjust the size of texts without compromising the quality of navigation [3]: 85). The ideal case here is the use of a CSS flexible textbox system, as this offers automatic scaling by default and thus the elements adapt directly to the viewport [6].

E. Theming

In this catalog of requirements, theming means that users are given the opportunity to adapt the user interface to their own requirements. This means, for example, that colors or font sizes can be adjusted, giving users the chance to influence the interface. This ensures that users can adapt their user interface to their respective, but usually very specific, needs and thus have a certain amount of design freedom, which can make their own work more efficient. Some users can differentiate certain colors better than others and some texts are difficult to perceive even with a font size of 24px. The ability to edit circumvents this and users have a degree of control over their user experience ([3], success criteria 1.4.4 & 1.4.8).

IV. CHECKLIST

A checklist was drawn up to review the implementation of the requirements, which serves as a guide to good and bad practices and can be used as an aid. It is recommended that the aspects below be considered programmatically in order to be as barrier-free as possible.

Color

- Good:
  - o Icons or texts as an alternative to pure color
  - o Add tooltips to hover animation -> with concise information
- Bad:

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- o Use of red/green/blue tones
- o Convey information only via colors

font

- Good:
- o normal text at least 24px in size, bold text at least 18.5px in size
- o Sufficient line, word and letter spacing
- o Short and concise information texts -> aligned left or right
- Bad:
- o Narrow and confusing text blocks
- o text blocks too long

Contrast

- Good:
- o at least a contrast ratio of 4.5:1 or higher for large texts
- o a contrast ratio of 7.5:1 or higher for normal texts
- o a contrast ratio of 7.5:1 or higher for the control element and its labeling
- Bad:
- o Background and foreground with the same color but different saturation
- o use the complementary contrast of red and green

Scalability

- Good:
- o Working with the Flexbox system -> automatic scaling and adjustment
- o Set up breakpoints
- o Assign values in units, such as %.
- Bad:
- o Make elements static or sticky
- o Fixed pixel values for elements independent of the font size

Theming

- Good:
- o Offer design freedom -> changing CSS values is possible
- Bad:
- o Fixed and unchangeable themes

V. Discussion and Conclusions

Colorblindness is one of the less considered impairments leading to inaccessibility of digital contents and web interaction. In education, at the workplace, and in consumer marketing, there is a need for an increased awareness of contrast and recognizability issues.

High contrast is also increasingly a prerequisite for artificial cognition of text. In combination with, among others, screen readability, alt text, magnification functionalities, contrast ensures a comprehensive readability of text and understanding of graphics.

This contribution exemplified how contrast checking tools can be used for optimization of usability, reception, and understanding. It devises a best-practice checklist for both designers and information technologists.

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Bridging the Digital Divide: Inclusive Digital Literacy for Individuals with Cognitive Disabilities

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***Abstract*— This paper introduces an innovative, semi-structured approach that is being implemented at DIGI Lab Siegen, where small groups of individuals with cognitive disabilities participate in a digital literacy course. The program is designed not only to impart technical knowledge but also to foster a sense of inclusion, as participants become familiar with key digital concepts and terminology. Furthermore, the initiative aims to facilitate digital inclusion, assistive technology adoption, and long-term sustainability by ensuring continued learning opportunities and community engagement. This concept, still in its early stages, raises questions about scalability, adaptability, and the long-term impact of semi-structured digital inclusion models.**

***Keywords*— digital literacy; cognitive disabilities; assistive technology; inclusion; digital divide.**

I. INTRODUCTION

Despite rapid advancements in Information and Communication Technologies (ICT), a significant portion of the population, particularly individuals with cognitive disabilities, remains at risk of digital exclusion [1]. Digital technologies have become an integral part of modern life, influencing everything from accessing government services to securing employment and maintaining social connections. However, for individuals with cognitive impairments, these advancements often serve to widen the gap rather than bridge it. Although employers may express inclusive intentions, the practical provision of digital tools and support for individuals with intellectual disabilities remains limited [2]. This lack of systemic support is evident not only in the workplace but also in educational settings: in many low- and middle-income countries, the implementation of adapted digital education for students with intellectual disabilities is still in its early stages, with only a minority of schools modifying curricula or providing appropriate digital tools and support [3].

This exclusion contributes to a growing digital divide, where affected individuals struggle to fully participate in modern society, reinforcing broader patterns of social inequality [4]. It is exacerbated by inflexible instructional formats and the limited adaptability of assistive technologies. Although accessibility standards have improved over time, people with cognitive disabilities still encounter numerous challenges in navigating most websites and digital applications [5]. Moreover, many digital inclusion initiatives continue to adopt standardized instructional models rooted in a "one-size-fits-all" philosophy [6]. These models often assume uniformity in learners' needs, learning styles, and cognitive abilities, which can hinder meaningful engagement for individuals with cognitive disabilities. To effectively support this group, more flexible and personalized instructional frameworks are needed.

DIGI Lab Siegen seeks to address this issue by providing a space where individuals with cognitive disabilities can collaboratively improve their digital literacy. The initiative is grounded in three core objectives:

- Empowering individuals with cognitive disabilities to use digital tools and actively participate in society.
- Enabling personalized adoption of assistive technologies by supporting guided, hands-on exploration and recommending suitable tools based on individual needs and observed interaction patterns.
- Supporting long-term digital engagement through an iterative, needs-responsive model anchored in local collaboration and practical contexts.

The rest of the paper is structured as follows. In Section II, we describe the structure and content of the semi-structured training sessions. Section III reflects on scalability and future adaptations. Section IV offers conclusions and outlines future work directions.

II. DIGITAL LITERACY TRAINING AT DIGI LAB SIEGEN

To develop an inclusive and adaptive digital learning environment, it was essential to identify participants whose needs and capabilities aligned with the goals of the program.

Participants were recruited through the University of Siegen's partnership with a local organization that supports individuals with cognitive disabilities. Age was not a selection criterion. Instead, participants were selected based on the following functional capabilities:

- The ability to understand simple instructions and express basic needs.
- The capacity to concentrate for at least 15 minutes.
- The willingness to collaborate in group settings and follow basic social norms.
- Sufficient motor skills to operate a keyboard or mouse, or the ability to interact with digital devices through alternative input methods such as voice control.

This approach enabled the inclusion of a diverse group of learners and laid the foundation for adaptive, individualized instruction.

The DIGI Lab Siegen model is built around a semi-structured, iterative approach. Participants were assigned to small groups of 3 to 4 individuals. Each session consisted of 45 minutes, followed by a 10-minute break and another 35-minute block. This structure is designed to align with typical attention spans observed among individuals with cognitive disabilities.

Unlike traditional digital literacy programs that assume a linear learning process, this initiative acknowledges that understanding develops gradually, and that full retention of information is not the primary goal. Instead, the emphasis is on fostering familiarity with technology, regular interaction, and confident navigation in digital environments.

Each session begins with a brief theoretical explanation, presented in simple language and supported by visual aids. To ensure comprehension, participants are encouraged to ask and answer questions. The session then moves on to skill-building games that reinforce core concepts such as clicking, dragging, tapping, and scrolling through playful interaction. Some games are designed with controlled failure mechanisms (e.g., ending after a set number of mistakes), while others permit continued play despite errors, thereby helping to reduce anxiety related to performance. If a particular game is found to be unsuitable or ineffective for a participant, a customized alternative is prepared for the following session. After the game segment, participants practice real-world tasks, followed by a short review and occasionally repetition of previous games to reinforce long-term learning. The program's flexibility allows content to be adjusted based on participants' individual progress. This learner-centered, responsive approach encourages participants to engage with digital environments confidently and autonomously.

One of the most important aspects of the DIGI Lab Siegen model is its focus on social and cognitive inclusion rather than solely on technical training. Through participation in semi-structured lessons, individuals with cognitive disabilities gain more than functional knowledge. They become better equipped to take part in everyday digital communication that might otherwise remain inaccessible to them. Even basic familiarity with digital concepts enhances their ability to interact with family members, caregivers, and broader social networks.

DIGI Lab Siegen also integrates assistive technology testing into its program. By continuously analyzing participants' needs and collaboratively evaluating existing solutions, the lab supports individuals in identifying the most effective and personalized tools for improving their interaction with technology.

III. SCALABILITY AND FUTURE CONSIDERATIONS

As the DIGI Lab Siegen model evolves, future research should explore how specific cognitive characteristics influence learning outcomes in semi-structured environments. Longitudinal observation may help uncover patterns in knowledge retention, attention, and motivation, providing a foundation for designing adaptive tools and instructional strategies that better align with individual learning needs.

Although DIGI Lab Siegen is currently a localized initiative, it offers a flexible framework that could be transferred to other contexts. This raises key questions for future implementation:

1) How can semi-structured digital literacy training be customized for different cognitive abilities and learning paces?

2) How can out-of-classroom interactions with technology be supported to encourage the practical application of acquired digital skills?

3) How can this approach be replicated in different cultural and socio-economic contexts?

By addressing these questions, future research and initiatives can build on the DIGI Lab Siegen experience to develop broader strategies for digital inclusion.

IV. CONCLUSION

Digital literacy programs for individuals with cognitive disabilities must go beyond conventional approaches. The DIGI Lab Siegen model offers a semi-structured, group-based learning experience that prioritizes familiarity, confidence, and inclusion over rigid technical mastery. Participants gain exposure to key digital concepts, helping them feel more engaged and integrated into society. While the initiative is still evolving, it provides a compelling case for rethinking digital literacy as an iterative, socially embedded process rather than a one-time educational intervention.

As this idea is being presented, a discussion is encouraged on ways in which semi-structured, small-group digital literacy training might be refined, expanded, and adapted to different contexts, ensuring that individuals with cognitive disabilities are not only users of technology but also confident participants in digital society.

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Assessing the Effectiveness of Acoustic Vehicle Alerting Systems (AVAS) for Pedestrians with Visual Disabilities

Insights from the EVA Survey

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***Abstract*— The increasing adoption of quiet Electric Vehicles (EVs) raises significant concerns about pedestrian safety, particularly for individuals who rely on auditory cues to navigate public spaces, such as those with visual disabilities. Although the United Nations Economic Commission for Europe (UNECE) Regulation No. 138 mandates the use of Acoustic Vehicle Alerting Systems (AVAS) in EVs to mitigate this risk, notable gaps remain between regulatory requirements and the real-world effectiveness of AVAS. This paper presents findings from the Electric Vehicle Acoustics (EVA) survey, which collected responses from pedestrians with and without visual disabilities to assess their experiences and perceptions of EV sounds. Statistical analysis, including median differences, effect sizes, and correlation matrices revealed disparities in how different pedestrian groups perceive AVAS effectiveness. The results underscore the need to refine AVAS design, ensuring improved real-world applicability and greater safety for visually disabled pedestrians.**

Keywords- inclusive design; electric vehicles; pedestrian safety.

I. INTRODUCTION

The increasing prevalence of Electric Vehicles (EVs) on public roads [1] presents both opportunities and challenges. While EVs travelling at low speed benefit noise reduction efforts in urban environments [2][3], their quiet operation also introduces safety risks [4][5][6], particularly for pedestrians at road crossings, in parking lots, and other environments where traffic speed is below 20- or 30-km/h. The challenge is most pronounced for individuals with visual disabilities [7][8] who rely exclusively on sound to detect vehicle presence and movement. For example, imagine a bustling and noisy city street where a quiet EV runs a red light just as a visually disabled pedestrian begins to cross.

Regulatory frameworks have attempted to address this issue through the mandating of the Acoustic Vehicle Alerting System (AVAS) - a system that artificially generates a sound signature using external speakers on modern EVs. Typically, such systems are engaged below certain speed limits (i.e., 20 km/h [9] or 30 km/h [10]), since above these speeds, tyre-on-road noise is considered sufficiently loud to make EVs acoustically comparable to combustion engine vehicles [11].

To assess the real-world effectiveness of AVAS, this paper is structured as follows: Section 2 outlines the regulatory context and technical background of AVAS implementation, highlighting its current limitations. Section 3 describes the design of the EVA survey, including participant criteria and the structure of the Likert-scale questions. Section 4 presents the statistical analysis of survey responses, incorporating descriptive statistics, effect sizes, and correlation matrices. Section 5 discusses the statistically significant differences in perception between pedestrians with and without visual disabilities. Finally, Section 6 offers directions for future research and calls for a reassessment of the fundamental design principles underpinning AVAS.

II. BACKGROUND

In the European Union, AVAS compliance is mandated under Regulation (EU) 2019/2144 [12], aligning closely with UNECE Regulation No. 138 [9], while the International Organization for Standardization (ISO) document ISO 16254 [13] provides the testing methodology to assess AVAS compliance. Regulatory approaches and testing frameworks vary globally, but the core objective remains the same: ensuring that EVs and hybrids operating in electric mode produce sufficient auditory cues for pedestrian to hear them.

Although regulatory implementation and compliance-testing represent significant progress, the real-world effectiveness of AVAS remains uncertain [14][15][16]. While AVAS is intended to enhance pedestrian safety, it is unclear whether current implementations fully meet the needs of pedestrians who rely entirely on auditory cues. Existing standards and regulations have established useful but rather broad requirements, such as minimum sound pressure levels as a function of speed (i.e., AVAS loudness); the inclusion of certain frequency components (i.e., AVAS tonality); and the requirement for AVAS when the EV is stationary but ready to move. Although UNECE regulation and the ISO standard have recently undergone important revisions and further refinement, they continue to offer significant flexibility to vehicle manufacturers - allowing them to generate unique AVAS signatures and in some cases, even allowing consumers to select from a palette of sound options. While all AVAS signatures are required to pass ISO 16254 and comply with UNECE 138, the degree of design flexibility raises concerns that AVAS is increasingly being used as a sonic-branding tool rather than as a safety feature [17][18].

Notably, most AVAS designs have not attempted to replicate the acoustic cues of internal combustion engines, which traditionally offered pedestrians reliable auditory information [19][20]. In response to this gap, several studies have explored more nuanced sound characteristics aimed at effectively alerting pedestrians to oncoming EVs, particularly those with sensory impairments. For example, e-scooter studies by Suzuki et al. [21] and work by Tyler [22] focus on the psychoacoustic and cognitive aspects of alert-inducing sound design, demonstrating that empirically derived acoustic profiles can improve pedestrian awareness and safety outcomes. Similarly, time-to-collision studies comparing AVAS signatures with internal combustion engine sounds have shown that AVAS fails to convey sufficient cues for pedestrians to accurately judge vehicle approach speed and estimate safe crossing distances [23][24]. These studies collectively highlight the importance of auditory familiarity, cue salience, and psychoacoustic subtleties in vehicle sound design. The present study builds on this work by providing structured survey data from pedestrians with and without visual impairments, offering new insights into how current AVAS implementations are perceived in uncontrolled, real-world environments.

Despite the role of AVAS in pedestrian safety, current standards and regulations have not systematically evaluated their effectiveness across diverse pedestrian groups, especially those who rely exclusively on sound when navigating built-up environments populated by EVs. Moreover, current frameworks cannot fully account for variations in ambient sound conditions, which can significantly impact a pedestrian's ability to detect an approaching EV. Looking ahead, the increasing adoption of EVs raises additional concerns about how pedestrians will distinguish between vehicles that pose an immediate safety risk and those that do not - especially for individuals unable to visually confirm vehicle movement. Addressing these gaps requires a structured evaluation of AVAS perception under real-world conditions. The present study serves as an initial step in this direction, gathering insights from pedestrians with and without visual disabilities regarding their experiences and perceptions of EV sounds.

III. Survey Design

The EVA survey was developed to assess pedestrian perceptions of AVAS, with particular focus on individuals who rely on auditory cues for navigation. The survey was disseminated through a combination of outreach to disabled persons organisations, relevant pedestrian safety mailing lists, and social media platforms. Ethical approval was obtained from the Ethics Committee of the Technological University of the Shannon prior to survey distribution.

Accessibility was a core consideration in the survey design. The online survey instrument was tested and optimised for use with screen readers. Participants were encouraged to use assistive technologies, and all survey components were structured to support independent completion by individuals with visual disabilities.

A. *Participant Criteria and Anonymity*

Participants were eligible to take part in the survey if they were aged 18 years or older, capable of providing informed consent, and had previously encountered one or more EVs (either by seeing or hearing them in operation). Visual disability was self-reported by participants via a survey question that also allowed respondents to indicate no visual disability. An indication of visual disability encompassed individuals with no vision as well as those with partial vision, in line with definitions provided by the National Disability Authority (NDA) Advice Paper [25].

To protect participant privacy, the survey did not collect any personally identifiable information and Internet Protocol (IP) tracking was disabled. All responses were reviewed to ensure anonymity was preserved. Participants were informed of the study's purpose, who comprised the research team, the institutions involved, and their right to withdraw at any time prior to submission. Submission of the completed survey was taken as a final consent to participate. Due to the anonymous nature of the data collection, responses could not be withdrawn after submission.

B. *Likert Statements*

The survey was structured to gather quantitative data on pedestrian experiences with EV sounds. It focused on ordinal questions using a 5-point Likert scale, where participants rated their level of agreement with statements related to AVAS perception, detectability, and effectiveness (Table I).

TABLE I. Nine Likert Statements used in the EVA Study

#	Statement
L1	I feel safe when I think there might be an EV close by.
L2	It is easy to notice an EV approaching because of its sound.
L3	Sounds made by EVs help me understand what the vehicle is doing
L4	I feel confident I understand an EV's next action based on its sound.
L5	I can react quickly to the sound of an EV when necessary.
L6	I find the sound of EVs pleasant.
L7	It takes little effort for me to listen to an EV's sound and understand what it is doing.
L8	I believe that the sound from all electric cars will be a positive thing for noise levels in busy cities and towns.
L9	Imagine you are standing on a busy street with lots of electric cars making sounds. Do you think it would be easy or hard to know when it is safe to cross the road?

Participants were asked to rate their level of agreement along the following scale (note L9 had a differently worded scale but complied with the negative to positive sentiment):

(1) I disagree a lot *(L9: Very difficult)*
(2) I disagree just a little *(L9: Difficult)*
(3) I don't know *(L9: Neither difficult or easy)*
(4) I agree just a little *(L9: Easy)*
(5) I agree a lot *(L9: Very easy)*

C. Data Preparation

To ensure accessibility and clarity, the survey wording was developed in line with National Adult Literacy Agency (NALA) guidelines [26], ensuring that participants of varying literacy levels could engage with the questions effectively.

A total of 86 survey responses were collected. Initial screening resulted in the removal of incomplete submissions, particularly those where respondents answered only one or two preliminary questions before exiting the survey. After this phase, 72 responses remained. Further data cleaning was performed to ensure that all participants had fully completed the Likert-scale questions necessary for statistical analysis, resulting in a final valid dataset of 54 responses.

The final dataset was split into two groups:

- **No Disability (ND)**: 33 participants
- **Visual Disability (VD)**: 21 participants

Other disability categories (such as hearing impairments or sound sensitivity) had insufficient sample sizes for comparative statistical analysis and were therefore excluded from the main group comparisons.

The cleaned dataset was stored in CSV format and subsequently used for statistical analysis using R Version 4.4.2.

IV. Survey Analysis

The analysis of the EVA survey data was conducted in two stages: an initial descriptive analysis, followed by inferential statistical testing. Descriptive statistics were used to summarise central tendencies and variability within the dataset, providing a broad view of general response patterns across the two participant groups (ND and VD). This included calculations of medians, interquartile ranges (IQRs), and effect sizes to highlight differences in perception. These results laid the foundation for the inferential analyses presented in Section 5, which assess the statistical significance of observed group-level differences.

A. Median Values and Interquartile Ranges

The first stage of analysis summarised the Likert-scale responses using the median and IQR for both ND and VD groups. These measures provide insights into the central tendencies and variations in responses across the groups.

A key trend observed was that the VD group generally reported lower median scores across most statements, indicating a stronger tendency to disagree with the survey statements compared to the ND group. In contrast, the ND group exhibited more neutral or positive responses, with medians ranging between 3 and 4, and displayed greater variation in their responses (see Figure 1).

Statements L1, L2, L3, and L7 showed the most pronounced differences, with VD participants consistently reporting strong disagreement. Notably, responses to L2, L4, and L7 were unanimous within the VD group, with an IQR of 0, indicating complete agreement in their perception that EV sounds were insufficient for safe navigation. In contrast, the ND group exhibited greater variation, with responses spanning a wider range.

Statements L6 and L8 displayed the most notable divergence in agreement, with ND participants tending to agree, while VD participants leaning towards neutrality or disagreement. This suggests that ND respondents may have a more favourable perception of AVAS in terms of their effectiveness and impact on urban noise levels, whereas VD participants were less convinced.

Overall, the results indicate that visually disabled participants are more critical of AVAS effectiveness, whereas sighted participants express a wider range of views, including some level of agreement. The strong uniformity of responses within the VD group suggests that their experiences with AVAS are more consistent, highlighting a potential inadequacy in current AVAS implementations.

B. Largest Differences in Medians and Effect Sizes

To identify the most significant differences in responses between the ND and VD groups, the absolute median difference was calculated alongside effect size using Cliff's Delta.

This analysis revealed that the largest disparities were observed in statements L1, L6, and L7, where VD participants strongly disagreed, whereas ND participants were more neutral or positive. The effect sizes for these statements (~0.60) indicate that these differences are statistically meaningful and not due to random variation.

Beyond these strongest disparities, moderate differences were found in statements L2, L3, L5, L8, and L9. The VD group was consistently more negative than the ND group, but the differences were less extreme, with effect sizes around 0.45. This suggests that while the two groups differ in their perceptions, the gap is narrower than in the highest-ranked statements.

Interestingly, statement L4 was the only one where both groups showed identical responses, with both strongly disagreeing. The small effect size (0.31) confirms that there is minimal variation in how this statement was perceived, indicating a shared viewpoint across both groups.

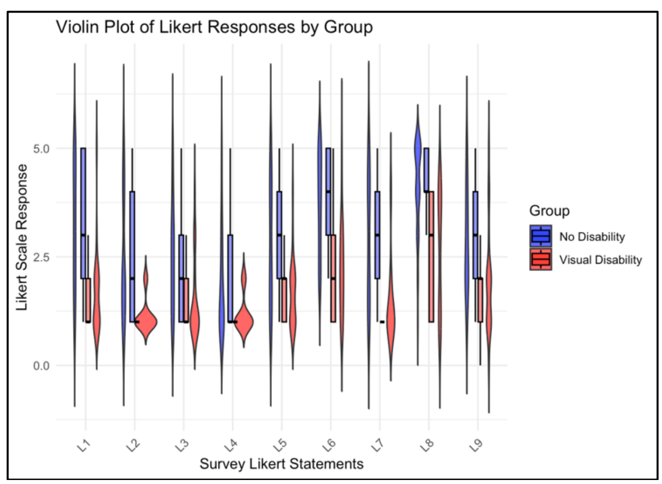

Figure 1. Violin plot showing Likert-scale response distributions for ND and VD groups across nine statements.

The width of each violin in Figure 1 indicates response density. The ND group (blue) shows greater variation in responses along the scale, while the VD group (red) demonstrates more compact distributions, particularly at the lower end of the Likert values - reflecting a consistently negative perception of AVAS. These patterns reinforce the trend observed in the median and effect size analysis: VD participants were generally more critical of AVAS effectiveness, while ND participants express more varied and sometimes more favourable views. The pronounced clustering in the VD group and the large effect sizes in key statements suggest that these differences are substantial and likely reflect real-world disparities in how AVAS is perceived and experienced by pedestrians who are visually-disabled.

C. Correlation Analysis

To further explore relationships between Likert-scale responses, Spearman's rank correlation was used to measure the strength and direction of associations between responses within each participant group. See Tables II and III for a summary of results.

TABLE II. SPEARMAN'S CORRELATION COEFFICIENTS ND GROUP

Likert Statements	Spearman's ρ (Correlation)	Interpretation
L1 & L9	0.68 (Strong)	Those who rate L1 in the positive also tend to rate L9 in the positive.
L2 & L3	0.62 (Strong)	Those who rate L2 in the positive also rate L3 in the positive.
L1 & L6	0.61 (Strong)	Responses for L1 are strongly related to L6.
L5 & L1	0.61 (Strong)	High agreement on L5 means high agreement on L1.
L4 & L3	0.48 (Moderate)	There is a moderate relationship between responses to L4 and L3.
L7 & L1	-0.08 (Weak/ Negative)	No meaningful relationship between L7 & L1.

TABLE III. SPEARMAN'S CORRELATION COEFFICIENTS VD GROUP

Likert Statements	Spearman's ρ (Correlation)	Interpretation
L3 & L4	0.73 (Very Strong)	Those who rate L3 high also rate L4 high.
L4 & L2	0.50 (Moderate)	Responses for L4 are moderately correlated with L2.
L6 & L3	0.49 (Moderate)	L6 responses are related to L3 responses.
L9 & L1	-0.09 (Weak)	No meaningful relationship.
L6 & L7	0.02 (Very Weak)	Almost no relationship.

Spearman correlation heatmaps are presented in Figures 2 and 3. These heatmaps visualise correlation coefficients in a matrix format, where warmer red colours indicate stronger positive correlations, while cooler blue colours indicate negative or weak correlations.

In relation to L1 (safety perception) and L9 (ease of detecting EVs in a busy street), these are strongly correlated (ρ = 0.68) in the ND group, suggesting participants who feel safer around EVs also find them easier to detect. In contrast, this correlation is actually absent in the VD group (ρ = -0.09), indicating that perceived safety and detectability are independent factors for these participants.

Correlation between L3 (understanding EV sound cues) and L4 (confidence in predicting EV movements) is very strong (ρ = 0.73) in the VD group, while it is only moderate (ρ = 0.48) in the ND group. This suggests that for visually disabled pedestrians, understanding an EV's sound is directly linked to their confidence in predicting vehicle movements, reinforcing the importance of AVAS effectiveness.

In the ND group, L6 (perception of EV sound pleasantness) and L7 (ease of interpreting EV sounds) are moderately correlated (ρ = 0.15). However, in the VD group, this correlation is almost non-existent (ρ = 0.02), suggesting that EV sound pleasantness does not significantly influence the ease of interpreting sound cues for visually impaired pedestrians.

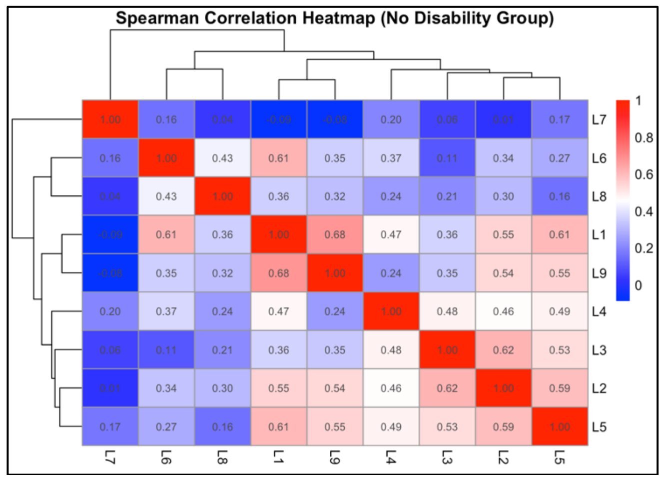

Figure 2. Spearman correlation heatmap for ND group Likert responses.

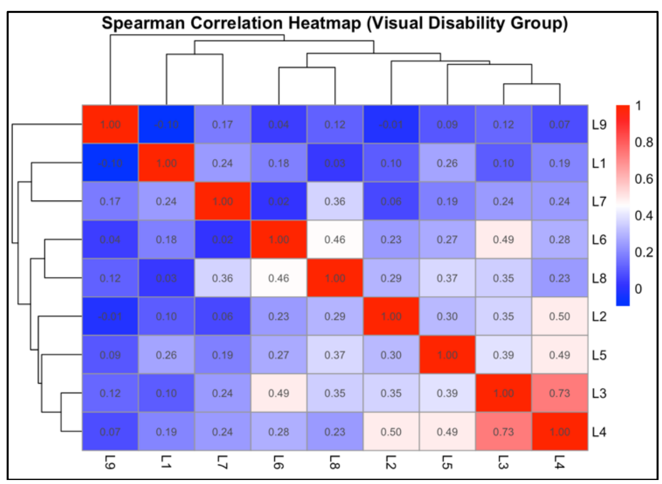

Figure 3. Spearman correlation heatmap for VD group Likert responses.

The two heatmaps reveal that some Likert statements exhibit strong correlations in one group but not the other, indicating fundamental differences in how pedestrians with and without visual disabilities process and respond to EV sounds. These group-specific patterns suggest that visually disabled pedestrians possibly interpret AVAS cues in a more interconnected and function-driven way, whereas sighted pedestrians may rely on a wider range of auditory and visual inputs, resulting in more varied perceptual relationships.

V. STATISTICAL SIGNIFICANCE ANALYSIS

To assess whether differences in AVAS perception between participant groups are statistically significant, a series of inferential statistical tests were conducted. These analyses build upon the descriptive statistics by determining whether observed differences are likely due to genuine group-level disparities rather than random variation. For inferential analysis, the Mann-Whitney U test was chosen because the ND and VD groups represent independent samples rather than repeated measures or matched pairs. The test is also appropriate for ordinal Likert-scale data and does not require assumptions of normality, making it suitable for detecting differences in central tendency between these two participant groups. Additionally, PERMANOVA (Permutational Multivariate Analysis of Variance) was employed to assess broader response patterns across all Likert items simultaneously. This method is also well-suited to non-parametric, ordinal data and enables the detection of group-level differences across multidimensional response profiles without assuming normality or homogeneity of variances.

A. Likert Comparisons between Groups

To assess whether the distributions of Likert-scale responses differed significantly between the ND and VD groups, a Mann-Whitney U (U) test was conducted for each Likert statement. Additionally, Rank-Biserial Correlation (r) was computed to measure the magnitude of effect size (Z), providing insight into the practical significance of observed differences – see Table IV.

TABLE IV. SUMMARY OF RESULTS FOR EACH LIKERT STATEMENT

#	U	p-value	Z	r	Interpretation
L1	554	0.00016	3.68	0.50	Strong significant difference; VD group rates much lower.
L2	555	< 0.0001	3.70	0.50	Significant difference; VD group more negative in response.
L3	507	0.0027	2.85	0.39	Moderate but significant difference.
L4	456	0.023	1.94	0.26	Weaker difference, though still statistically significant.
L5	503	0.0040	2.78	0.38	Significant difference, though less extreme than L1 & L2.
L6	563.5	< 0.0001	3.85	0.52	Strong difference; VD group disagrees more.
L7	549.5	0.00015	3.60	0.49	Strong difference; VD group rates significantly lower.
L8	552	0.00016	3.65	0.50	Clear difference, VD group more neutral or negative.
L9	461.5	0.013	2.41	0.33	Medium-level difference between groups.

The results indicate statistically significant differences between the ND and VD groups for all Likert statements. The strongest differences were observed for L1 (perceived safety), L2 (detectability of EVs), L6 (pleasantness of EV sounds), and L7 (effort required to interpret AVAS cues), all of which had large effect sizes (r ≈ 0.50 or above).

Moderate differences were found for L3, L5, and L9, while L4 showed the weakest but still significant difference. This suggests that while both groups shared concerns about AVAS effectiveness, visually disabled participants rated their experience more negatively.

B. Multivariate Analysis - PERMANOVA

Given the significant group differences observed in individual Likert responses, a PERMANOVA was conducted to help determine whether overall response patterns across all Likert statements differed significantly between groups. A Gower distance matrix was used, as it is well-suited for mixed and ordinal data. Group differences was the only evaluation under consideration, hence 1 Degree of freedom (Df) in the analysis. The results are summarised in Table V.

TABLE V. SUMMARY OF RESULTS FOR EACH LIKERT STATEMENT

Factor	Df	Sum of Squares	R^2 (%)	F-Stat	p-value	Comment
Group ND vs VD	1	1.0546	27.1	19.37	< 0.001	Significant difference between groups.
Residual	52	2.8311	72.9	-	-	Remaining variance due to individual differences.

The grouping variable (ND vs VD) explains 27.1% of the variance ($R^2 = 0.2714$) in the dataset. The F-statistic (19.37) is high, indicating a strong effect and the p-value (< 0.001) is highly significant, confirming that the overall response pattern differs substantially between groups.

While 27.1% of the variance is attributed to group differences, the remaining 72.9% suggests that additional factors such as age or individual attitudes toward EVs may potentially also contribute to variability.

VI. CONCLUSION

The findings from the EVA survey highlight significant disparities in how different pedestrian groups experience AVAS. The statistical analysis revealed that visually disabled pedestrians consistently rated AVAS as less effective in providing the necessary auditory cues for safe navigation compared to those without visual impairments. These results raise concerns regarding the adequacy of current AVAS implementations in real-world pedestrian environments.

From a regulatory perspective, while UNECE 138 and ISO 16254 establish fundamental requirements for AVAS and its compliance testing, they do not mandate in-depth psychoacoustic design-criteria that would ensure AVAS sounds are intuitively interpretable by all pedestrians. Flexibility in AVAS design may contribute to inconsistencies in pedestrian responses, as evidenced by the survey results. Additionally, the analysis of response variability suggests that visually disabled participants were more consistent in their perception of AVAS inadequacies, whereas sighted participants exhibited a broader range of opinions, likely influenced by their ability to rely on visual cues.

The inferential statistical analysis further confirms that the differences in AVAS perception between the two groups are statistically significant, with large effect sizes and very small p-values for key Likert statements related to detectability, safety, and confidence in interpreting AVAS signals. The multivariate analysis reinforces these findings, demonstrating that response patterns between the two groups are distinct, where participants with a visual disability exhibiting more clustered responses indicating a uniform dissatisfaction with AVAS effectiveness.

While these findings provide important insights, the study has several limitations that should be acknowledged. First, the sample size (particularly for the VD group) was modest, which may limit the generalisability of the results. Nonetheless, the presence of very small p-values and large effect sizes across multiple Likert items suggests that the observed differences are both statistically and practically meaningful, which goes some way toward mitigating this concern. Second, visual disability was self-reported without clinical verification. Although this approach aligns with inclusive research practices and respects participant anonymity, it may introduce variability in how individuals interpret and report their disability. Third, although the online survey was optimised for accessibility, individuals with more severe impairments or limited digital access may have been underrepresented. Additionally, the survey relied on structured, close-ended responses, and did not capture long-form or qualitative feedback that could provide deeper insight into participants' reasoning. This limited the ability to explore contextual factors or explanatory themes underlying their perceptions. Future phases of the EVA study will address this by incorporating open-ended prompts with subsequent sentiment analyses to enrich the understanding of how AVAS is experienced across diverse pedestrian groups. Finally, as the study focused on self-reported perceptions, future research would benefit from triangulating these findings with behavioural or auditory-response data collected under controlled or real-world conditions.

Despite the limitations outlined above, the findings strongly support the need to reassess AVAS design, placing greater emphasis on psychoacoustic principles to ensure that sounds are both detectable and interpretable. In particular, future design efforts should prioritise reliability and consistency for pedestrians who rely exclusively on auditory cues for situational awareness. To this end, future EVA research will involve controlled auditory experiments to evaluate AVAS effectiveness across diverse urban soundscapes and will explore the development of universal-design sound profiles that prioritise functional safety over branding considerations. These profiles will draw more explicitly on ecological psychoacoustic principles - for example, incorporating auditory cues that trigger innate perceptual responses, such as the urgency conveyed by looming sounds [27], or applying design strategies that account for asymmetry in frequency–intensity combinations and other nuanced psychoacoustic traits [28].

Psychoacoustic and ecological approaches to sound design have long been recognised as effective strategies for enhancing the communicative power of sound. These approaches aim to make auditory cues more reliable, intuitive, and universally understandable - particularly when conveying information of varying urgency or importance to listeners [29][30][31]. In this context, ecological psychoacoustics offers a valuable framework for balancing perceptual clarity with user comfort [32], making it especially relevant to the future design of AVAS systems.

In addition to this, further research will be required to examine how long-term exposure to AVAS affects pedestrian adaptation, risk perception, and behavioural response. Ultimately, advancing AVAS through perceptually grounded, inclusive design can help ensure that the growing presence of EVs enhances safety for all.

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Taighde Éireann
Research Ireland

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