This article has been accepted for publication in IEEE Transactions on Visualization and Computer Graphics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TVCG.2024.3356566

Beyond Vision Impairments: Redefining the Scope of Accessible Data Representations

Brianna Lynn Wimer, Laura South, Keke Wu, Danielle Albers Szafir, Michelle A. Borkin, Ronald Metoyer

***Abstract*—The increasing ubiquity of data in everyday life has elevated the importance of data literacy and accessible data representations, particularly for individuals with disabilities. While prior research predominantly focuses on the needs of the visually impaired, our survey aims to broaden this scope by investigating accessible data representations across a more inclusive spectrum of disabilities. After conducting a systematic review of 152 accessible data representation papers from ACM and IEEE databases, we found that roughly 78% of existing articles center on vision impairments. In this paper, we conduct a comprehensive review of the remaining 22% of papers focused on underrepresented disability communities. We developed categorical dimensions based on accessibility, visualization, and human-computer interaction to classify the papers. These dimensions include the community of focus, issues addressed, contribution type, study methods, participants, data type, visualization type, and data domain. Our work redefines *accessible data representations* by illustrating their application for disabilities beyond those related to vision. Building on our literature review, we identify and discuss opportunities for future research in accessible data representations. All supplemental materials are available at https://osf.io/yv4xm/?view_only=7b36a3fbf7a14b3888029966faa3def9.**

***Index Terms*—Accessibility, Data Representations.**

I. Introduction

Data plays a crucial role in enabling individuals to explore information about themselves, their communities, and topics of personal relevance and importance [1]. With the growing utilization of data in everyday life, data literacy, once primarily confined to scientific professionals and journalists, has now evolved as an essential skill for the general population [2]. Individuals utilize data to formulate informed decisions across many domains, including health, finance, and current events [1]. Historically, visual representations, typical data visualizations, have been the primary tool to render data more comprehensible to the general public. However, data visualizations have evolved beyond traditional visual representations, including innovative ways to engage auditory and tactile modalities. These multimodal approaches provide immersive insights, enhancing our understanding and interaction with complex data sets. Such an expansion in multimodal data representations is partly attributable to the need for accessibility, as conventional visualizations may pose challenges for individuals with disabilities [3], necessitating the exploration of alternative representations for data.

Individuals with disabilities frequently encounter limitations in accessing, engaging with, and interpreting complex data [4]. Addressing this disparity is critical because it is paramount that all societal members, irrespective of their abilities, are accorded uniform access to information and the tools required to extract meaningful insights from it. Efforts to augment accessibility in data representations have been predominately directed towards individuals from blind or low-vision (BLV) communities [5]. However, individuals with non-vision disabilities can also benefit from accessible data representations. For example, wheelchair users may utilize geographical maps to access information about sidewalk accessibility [6]. Those with cognitive disabilities can interpret their behavioral data through specialized visualizations [7]. Additionally, for deaf and hard-of-hearing (DHH) individuals, word clouds can present auditory data from hybrid meetings to be more accessible [8].

Building on these insights, our research seeks to expand the scope of accessible data representation beyond the traditional focus on the BLV communities. While previous studies have predominantly centered on data representations tailored for visually impaired individuals [5], [9], we aim to take a more inclusive approach. Our research explores accessible data representation across a broader spectrum of disabilities, delving into historically overlooked areas. The objective of this paper is distinct: to investigate underrepresented communities and better understand how accessible data representations have supported people with various disabilities.

To achieve this, we systematically analyzed literature from ACM and IEEE databases. Of the 152 papers reviewed, 78% predominantly focus on vision impairments. However, the remaining 22% demonstrated a diverse range of disabilities, such as motor or physical impairments, cognitive and perceptual disabilities, neurological conditions, chronic illnesses, and issues

B. Wimer and R. Metoyer are with the Department of Computer Science and Engineering at the University of Notre Dame. Notre Dame, IN, 46556 USA. E-mail: {bwimer, rmetoyer}@nd.edu

L. South and M. Borkin are with the Khoury College of Computer Sciences at Northeastern University. Boston, MA 02115 USA. E-mail: {south.l, m.borkin}@northeastern.edu

K. Wu and D. Szafir are with the Department of Computer Science at the University of North Carolina-Chapel Hill. Chapel Hill, NC, 27599 USA. E-mail: {kekewu, dnszafir}@cs.unc.edu

related to older adults. This diversity underscores the importance of a comprehensive review to understand the various research objectives, the types of data representations utilized, and the methodologies employed in accessible data representation.

In summary, we present three contributions: 1) A thorough overview of trends in accessible data representations, 2) A new taxonomy specifically for non-vision impairments, and 3) Insights into future research opportunities and challenges in this field. Our work redefines the scope of accessible data representations beyond vision impairments, highlighting the need for accessible data representations that cater to a broader spectrum of disabilities and present a preliminary framework for accessible data representations, building on the foundational work of Kim et al [5].

II. Background

A. Disability & Accessibility

According to the World Health Organization (WHO), approximately 16% of the world's population lives with some form of disability [10]. This group is inherently diverse, with each individual facing a unique set of challenges that may result in lower life expectancies, compromised health statuses, and greater daily limitations compared to those without disabilities [10].

Technological interventions can empower people with disabilities, producing tailored solutions to specific challenges. Accessibility research, committed to developing and adapting technologies for individuals with disabilities, has gained considerable momentum in recent years [11]. Significant progress includes the development of theoretical frameworks and guidelines (e.g., [12], [13]), the innovation of new techniques (e.g., [14], [15]), and the implementation of practical applications in various areas (e.g., [16], [17]).

A significant change in accessibility has been the shift toward ability-focused design solutions rather than those centered on disabilities. Wobbrock et al. introduced the concept of *Ability-Based Design*, which repositions abilities as the critical factor in design considerations [12]. Quintero further emphasizes the crucial role of participatory and collaborative approaches when creating accessible technologies [18]. These advancements are not limited to a single application; they span various domains from educational tools [19] to navigation aids [20], serving diverse communities and advancing the overarching goal of digital equity.

Despite recent progress, the issue of data accessibility—defined here as the ease with which people can access, understand, and interact with data—has only recently started to receive significant attention [3]. Existing research provides limited insight into the unique data challenges faced by individuals with various disabilities. There is also a lack of guidance on designing accessible data representations to serve the specific needs of these diverse groups. Our study aims to fill this gap, focusing not just on vision impairments but on a broader range of disabilities to make data more universally accessible.

B. Data Visualization Accessibility

In this subsection, we focus specifically on the accessibility of data visualizations, representing the most prevalent form of data representation. Recent research in this area has increasingly shifted towards improving the accessibility of data visualizations, spurred by a growing awareness of its importance [4]. Research on accessible data visualization has primarily focused on meeting the needs of individuals with vision impairments. Key areas of study include exploring screen reader user experiences with visualizations [21], investigating touch-based accessible graphics [9], examining optimal ways to communicate information through various modalities [22], and assessing the real-world accessibility of visualizations [23].

Since traditional data visualizations heavily rely on visual cues, researchers have explored alternative modalities to make visualizations more inclusive. These alternatives include speech-based interfaces [24]–[26], sonification techniques [27], and tactile or haptic displays [28]–[31]. These innovations not only enhance the accessibility of data visualization but also contribute to a broader understanding of multimodal information processing [3], [5], [32]. Alternative modalities have been instrumental in expanding accessible data visualization research, showcasing the potential to benefit not only individuals with vision impairments but also those whose physical disabilities render it challenging to engage with data visualizations using conventional input and output methods [33]. As accessible data visualization continues to evolve, research continues to focus on people with vision impairments [3], [4]. While researchers have begun to recognize data access as an equity issue for various disabilities such as auditory, cognitive, and motor impairments [4], [34], these areas have received less attention than vision-related disabilities.

Adaptive design principles that address the users' unique needs with sensory, motor, or cognitive impairments make data representations more inclusive within digital environments. For instance, individuals with motor disabilities can benefit from specialized data representations of maps. These could include real-time data on wheelchair-accessible routes, easing their navigation through urban settings [6]. Universal accessibility in interacting with these data representations remains crucial [33]. Such accessibility equips individuals with motor disabilities to engage with data and navigate their environment confidently.

Similarly, adapting visualization design guidelines to support people with cognitive disabilities can improve their information processing and mitigates specific challenges [35]. Integrating these considerations into visualization design enhances user sensemaking and contributes to a more inclusive information landscape. This inclusivity empowers people with disabilities to participate fully in various aspects of modern life, from education and employment to personal decision-making and social engagement.

While these efforts are significant, it is essential to acknowledge that the challenges faced by underrepresented communities with varying disabilities may differ from those commonly addressed for the BLV population. Solutions effective for the BLV community may not universally apply to people with other forms of impairment. To this end, our comprehensive review aims to explore and highlight the varied accessibility needs across a diverse range of disabilities. By doing so, we seek to synthesize the challenges and solutions specific to these underrepresented groups, encouraging further research and fostering a more nuanced understanding of accessibility in data representations.

III. Methodology

We employed a systematic review approach following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology [36]. The PRISMA guidelines provide a comprehensive framework to ensure transparency, replicability, and rigor in the identification, screening, and synthesis of relevant studies. The methodology comprised three primary stages: (1) identification of studies, (2) dataset creation, and (3) data synthesis and analysis. In addition, we provide our dataset within the supplemental materials (also available online at https://osf.io/yv4xm/?view_only=7b36a3fbf7a14b3888029966faa3def9).

A. Identification of Papers

This study focuses on accessible data representations for people with disabilities and emphasizes the often overlooked needs of individuals with non-visual disabilities. The multidisciplinary nature of the papers collected for this review encompasses research from visualization, human-computer interaction(HCI), and accessibility communities. Thus, combining research across multiple proceedings, we defined ACM Digital Library and IEEE Xplore databases as the most relevant for our review. Furthermore, we limited our analysis to papers published between January 2000 and December 2022. The search strategy encompassed keywords and boolean operators to identify potentially relevant articles within the categories of visualization, accessibility, and disability. Relevant studies were retrieved using the search query:

```
(("visualization" OR "visualisation"
OR "graph" OR "chart") AND
("accessible" OR "accessibility" OR
"inclusi*") AND ("disability" OR
"disabled" OR "impair*"))
```

We also specifically searched IEEE TVCG, VIS, TOCHI, CHI, TOACCESS, ASSETS, CSCW, and CGF (EuroVis) using a broader search query with keywords in the same categories. The last search was concluded in December 2022.

B. Dataset Creation

After removing duplicates, 913 records were identified through database searches, constituting our initial corpus. Three researchers divided the initial corpus to independently screen the titles and abstracts of the identified records against pre-defined inclusion and exclusion criteria. When necessary, the main text was also reviewed to determine the eligibility of each paper for inclusion in the final corpus based on our criteria. The inclusion criteria for this review are presented below:

- Focus on accessibility pertaining to disabilities and/or impairments
- Address the accessibility of data-driven representations

The exclusion criteria were:

- Artifacts previously published in another publication
- Papers not reported in English

Any uncertainties and disagreements between researchers were resolved through discussion. Following the initial screening, three researchers retrieved the full texts of the selected articles and assessed them for eligibility. Ultimately, 152 articles were included in the final corpus for our systematic review.

To conduct a more focused investigation of non-visual accessibility, we created a new dataset from a subset of our initial collection, specifically addressing underrepresented communities. To achieve this, three researchers divided the collection of 152 papers and examined titles and abstracts to identify articles not exclusively centered on vision impairments. Papers were considered eligible for inclusion if they either addressed a non-visual disability, accessibility from a non-specific perspective (i.e., without focusing on a single particular disability), or discussed vision impairments in conjunction with at least one other non-visual disability.

The newly created dataset comprised 34 papers selected based on their emphasis on non-visual accessibility. This selection facilitated a more comprehensive examination of the unique challenges and opportunities that underrepresented disability communities face within accessible data representations.

C. Data Synthesis and Analysis

We carried out quantitative and qualitative analyses on our two datasets: the unfiltered dataset of 152 papers to provide an overview of the current state of research in accessible data representation and a more detailed analysis of our 34-paper corpus.

1) Analyzing Trends in Accessible Data Representations: Our initial investigation of the 152 papers aimed to provide an overview of accessible data representation research, focusing on understanding the target populations and the field's growth trajectory in recent years. The quantitative aspect of this investigation entailed gathering paper characteristics, such as the target audience and publication year, to appraise the literature systematically. This approach enabled us to offer key trends and insights in accessible data representations.

2) Taxonomy of Accessible Data Representations for Non-Vision Disabilities: To complement the overview of our initial investigation, we conducted a qualitative examination of the 34 articles within our focused subset. Our primary objective in this systematic review is to present a comprehensive perspective on how accessible data representations diverge across various non-visual disabilities. Consequently, we employed inductive thematic analysis [37] to create a classification schema for our focused dataset.

Our thematic analysis adhered to the six principal stages delineated by Braun and Clarke [37]: (1) familiarization with the data, (2) generation of preliminary codes, (3) exploration for themes (in this context, dimensions of accessible data representations), (4) assessment of the themes, (5) definition and denomination of the themes into dimensions, and (6) completion of the final report. The refined subset was divided among three researchers to code the papers, generating preliminary codes independently and subsequently meeting weekly to reassess codes throughout the corpus. During these meetings, the researchers discussed any uncertainties and established consistency among their codes.

This approach allowed us to review the articles multiple times, helping us refine key themes into dimensions and identify their connections. We extracted information regarding research objective (e.g. issues addressed, contribution type), research methodology (e.g., research methods, participants involved, and sample sizes), and data representation (e.g., data types utilized, visualization type, and the data domain) from each of the 34 papers.

IV. Trends in Accessible Data Representation: Target Audience and Publication Trends

We first characterize the state of accessible data representation research in terms of target audience and years when papers were published.

A. Target Audience

An overwhelming 78.3% (N=119) of the 152-paper corpus focuses on the unique needs of individuals who are blind or have low vision. As illustrated in Table I, research on accessible data representations disproportionately focuses on visual accessibility. The remaining communities receive disproportionately less attention, constituting less than 22% of the reviewed literature. Of the 119 papers focusing on the BLV community, we found only one study that was not exclusively centered on this group (e.g., [38]).

Target Audiences	Papers w/ Code	This Code Only
BLV	119 (78.3%)	118 (77.6%)
Motor/Physical	12 (7.9%)	8 (5.3%)
Older Adults	6 (4.0%)	3 (2.0%)
DHH	5 (3.3%)	5 (3.3%)
General Disability	5 (3.3%)	5 (3.3%)
Autism	2 (1.3%)	1 (0.7%)
Cognitive	2 (1.3%)	1 (0.7%)
IDD	2 (1.3%)	0 (0.0%)
Learning Disabilities	2 (1.3%)	2 (1.3%)
Other	2 (1.3%)	2 (1.3%)
ADHD	1 (0.7%)	1 (0.7%)

TABLE I
FREQUENCY OF CODES IN *target audience* FOR THE 152-PAPER CORPUS. 'THIS CODE ONLY' COUNTS INSTANCES WHERE THE CODE WAS APPLIED IN ISOLATION, NOT ALONGSIDE ANY OTHER CODES IN THIS DIMENSION.

B. Publication Trends

We analyzed the chronological distribution of all 152 papers in our dataset to understand historical trends. As depicted in Figure 1, research in accessible data is growing, reflected by increased publications. Most strikingly, the volume of papers in 2021 nearly doubled compared to the previous year, a surge we believe is partly attributable to the heightened public need for understandable data during the COVID-19 pandemic. During this global crisis, governments extensively utilized data visualizations for communicating crucial information, elevating public awareness, and forecasting future outcomes, making intricate data more accessible to a broader audience [39]. However, the pandemic exposed the limitations of existing data visualization practices and served as a catalyst for change in terms of accessibility, mainly when a significant portion of the population lacked adequate access to vital information [4].

V. Classification Scheme

Our taxonomy, developed at the intersection of visualization, human-computer interaction (HCI), and accessibility, aims to establish a comprehensive taxonomy for categorizing accessible data representations. This taxonomy incorporates classifications from each area, including aspects of visualization [40], accessibility [11], and HCI [41], [42].

The development of this taxonomy involved iterative rounds of open coding, leading to the identification of eight dimensions: (1) **community of focus**, (2) **issues**

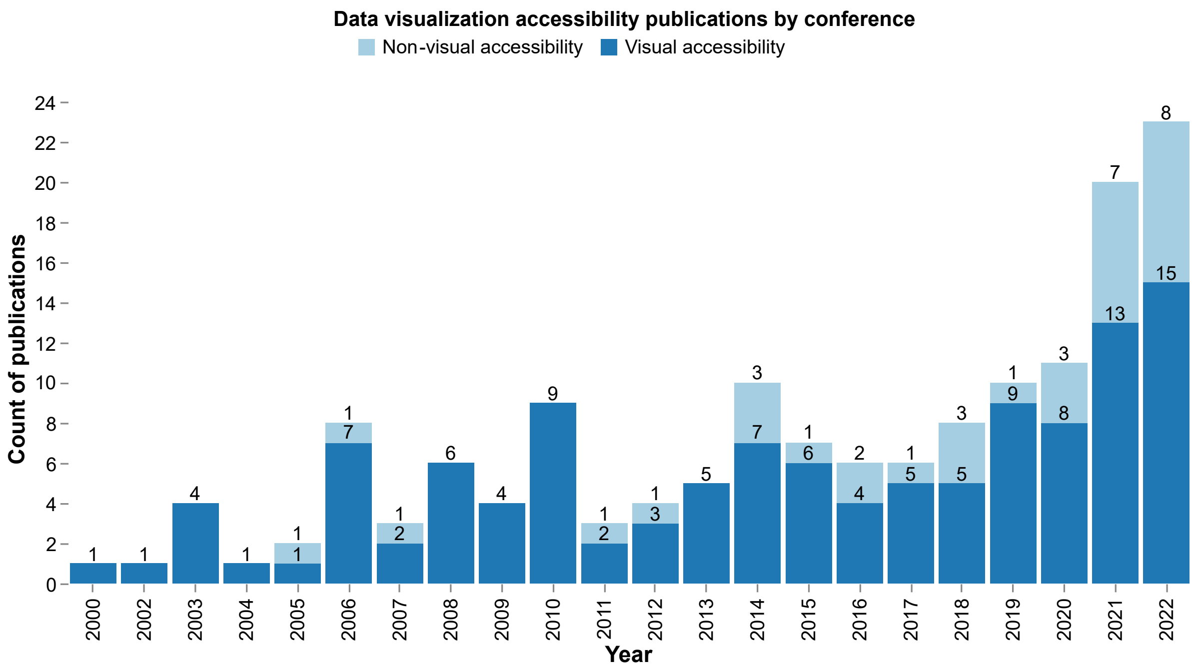

Fig. 1. An overview of the collected papers, categorized by year and community of focus, with a particular emphasis on either the BLV population for visual accessibility or underrepresented communities for non-visual accessibility.

addressed, (3) **contribution type**, (4) **study methods**, (5) **participants involved**, (6) **data type**, (7) **visualization type**, and (8) **data domain**. To streamline our analysis, we have categorized the eight dimensions into three distinct groups, each representing a core aspect of the surveyed research. The first group, *research objectives*, encompasses dimensions that define the goals and target communities of the studies. The second, *research methodology*, includes dimensions related to the methods and participants involved in the research process. Finally, *data representations* covers dimensions that describe the types and domains of data used. This structured grouping is visually represented in Figure 3, aiding in a clearer understanding of our taxonomy's framework.

This section presents our classification scheme to our survey of 34 papers focusing on non-vision impairments. Detailed definitions for each of the eight dimensions and 64 codes in our taxonomy are available in the Supplementary Materials. Complementing this, Figure 2 gives an overview of our classification scheme.

A. Research Objectives

1) Community of Focus: We included the *community of focus* dimension, inspired by Mack et al. [11], to identify the "accessibility-related population or community being studied or positioned by the authors as benefiting from the research [11]." Our analysis revealed various terminologies and groupings used to describe these communities. Notably, many studies addressed multiple disability communities simultaneously. For example, research on older adults often encompassed motor/physical and cognitive impairments. Similarly, studies on intellectual or developmental disorders (IDD) frequently included motor/physical impairments and autism.

Like Mack et al. [11], we faced the most inconsistencies around neurodiverse populations in our corpus. To address this and more accurately represent the variety of groups studied, we followed the authors' original descriptions of their targeted communities. This led us to distinguish between communities that are often collectively addressed, such as IDD from autism (e.g., [35]). This decision allowed us to achieve a more detailed and inclusive classification, particularly for neurodiverse and cognition-related disabilities, thus ensuring a finer-grained categorization in our taxonomy.

In our original corpus of 152 papers, only 22% (N=34) of papers focused on accessible data representation research for non-vision disabilities. Among these non-vision disabilities, we identified eleven distinct communities, as listed in Table II. The most represented communities were motor and physical disabilities (35.3%, N=12), followed by those targeting older adults (17.6%, N=6). Furthermore, research on the DHH community and studies with a broader focus on general disabilities each received similar levels of attention, accounting for 14.7% (N=5) of the papers. Papers categorized under *general* disability primarily focused on accessibility concerns pertinent to a wide spectrum of disabilities. This broad category encom-

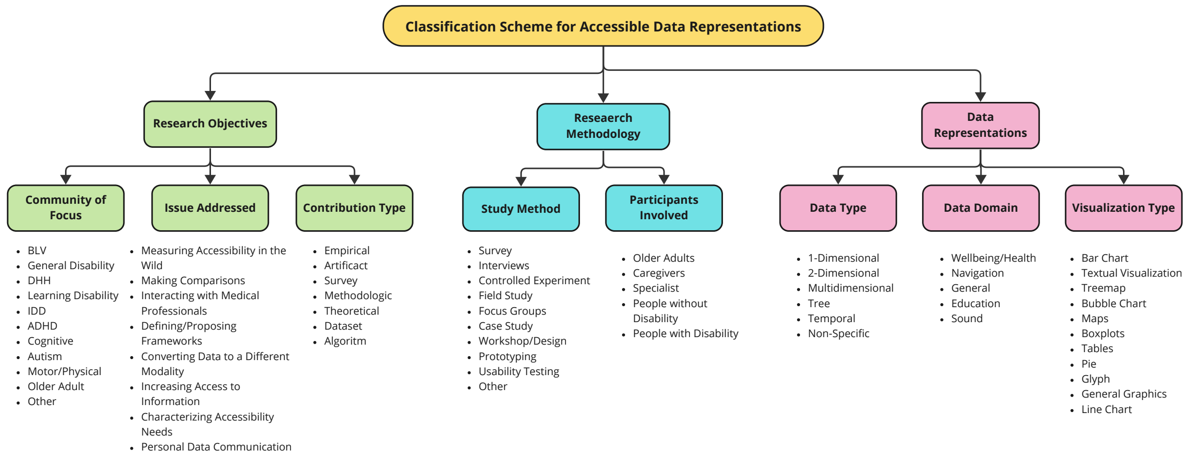

Fig. 2. Our comprehensive classification scheme for accessible data representations, comprising three overarching groups, further divided into eight dimensions and encompassing a total of 64 specific codes.

passes research addressing various issues: from the development of accessible data components for academic publications [43] to investigations into sociotechnical aspects [30], and the establishment of accessibility standards in data representations [44]. Other communities received less consideration, encompassing individuals with cognitive impairments (5.9%, N=2), IDD (5.9%, N=2), autism (5.9%, N=2), learning disabilities (5.9%, N=2), and attention deficit hyperactivity disorder (ADHD) (2.9%, N=1). In line with Mack et al. [11], the *other* classification, accounting for 5.9% (N=2) of our articles, was used to identify emerging and underrepresented areas in accessibility research. This category, specifically assigned to studies focusing on individuals with chronic [45] and neurological conditions [46], highlights the necessity of expanding research to include a broader range of disabilities. It underscores the potential for growth in areas that are currently not well-represented in accessibility research either.

2) Issues Addressed: To better understand the scope of research in accessible data representations, we analyzed the research objectives of papers within our dataset. This dimension was inspired by Mack et al. [11] categorization of common issues researchers attempt to address in accessibility literature. We classified each paper according to its primary objective, whether it was to make data representations more accessible or to use these representations to facilitate better access to information or places for people with disabilities.

We identified eight issues addressed by researchers. Our analysis revealed that the most prominent goals in current research are enhancing access to the physical world (26.47%, N=9), conveying personal data (20.59%, N=7), and devising accessibility frameworks (17.65%, N=6)—see Table III. Furthermore, we identified five additional issues researcher attempted to tackle: transforming data into alternative modalities (14.71%, N=5), facilitating interactions with medical professionals (14.71%, N=5), assessing accessibility "in the wild" (8.82%, N=3), comparing disabled and non-disabled populations (8.82%, N=3), and characterizing accessibility requirements (5.88%, N=2).

Community of Focus	**Papers w/ Code**	**This Code Only**
Motor/Physical	12 (35.29%)	8 (23.5%)
Older Adults	6 (17.6%)	3 (8.8%)
DHH	5 (14.7%)	5 (14.7%)
General Disability	5 (14.7%)	5 (14.7%)
Autism	2 (5.9%)	1 (2.9%)
Cognitive	2 (5.9%)	1 (2.9%)
IDD	2 (5.9%)	0 (0.0%)
Learning Disabilities	2 (5.9%)	2 (5.9%)
Other	2 (5.9%)	2 (5.9%)
ADHD	1 (2.9%)	1 (2.9%)
BLV	1 (2.94%)	0 (0.0%)

TABLE II
FREQUENCY OF CODES IN *community of focus* FOR THE 34-PAPER CORPUS. 'THIS CODE ONLY' COUNTS INSTANCES WHERE THE CODE WAS APPLIED IN ISOLATION, NOT ALONGSIDE ANY OTHER CODES IN THIS DIMENSION.

Interestingly, the identified issues addressed were not consistently associated directly with specific communities. Enhancing access to the physical world, which encompasses aspects such as neighborhood accessibility [47] and public transportation access [48], predominantly emerged in papers concentrating on motor/physical disabilities (77.8% N=7/9). However, four papers also examined augmenting physical world access for individuals with cognitive impairments, older adults, BLV, and the general disability community. Analogously, personal data communication emerged as the most diverse issue addressed, spanning five communities: older adults, cognitive impairments, ADHD, autism, and others. Personal data may encompass a range of information, including physiological data [45], mental engagement [49], behaviors [7], or performance [50], but the communication of personal data consistently involves monitoring an individual's data to communicate this information to users, caregivers, or medical professionals. This process, tailored for unique requirements, frequently deals with data that is particularly relevant for individuals with disabilities, a type of data that is generally less prevalent in the non-disabled population. For instance, it might involve monitoring cognitive function in individuals with cognitive impairments, which is not a common concern for those without such conditions [49].

Moreover, the transformation of data into alternative modalities was particularly prominent in research focused on the DHH community (80%, N=4/5), demonstrating how speech data and sound localization can be transposed into textual visualizations (e.g., word clouds [8] or visual representations to indicate sound characteristics [51]). This issue is similarly crucial in the BLV communities, where transforming data into accessible representations (e.g., tactile,auditory) is essential for bridging sensory gaps and enhancing accessibility [4], [21]. Meanwhile, the creation or proposal of accessible frameworks was more commonly associated with studies addressing general disabilities (66%, N=4/6). This finding highlights how, although research objectives may differ, there is often an overlap in addressing accessibility across different disability communities, emphasizing the potential of these frameworks to provide guidelines for accessible data beyond a singular disability focus.

By integrating these findings with our *communities of focus* dimension, we uncovered opportunities for creating accessible data representation solutions that can benefit multiple disability communities. These insights underscore the importance of tailoring data representations to specific groups and recognizing shared challenges that can drive broader advancements in data accessibility.

Issue Addressed	Papers w/ Code`	This Code Only
Increasing Physical World Access	9 (26.5%)	9 (26.5%)
Personal Data Communication	7 (20.6%)	5 (14.7%)
Devising/Proposing Frameworks	6 (17.7%)	4 (11.7%)
Converting Data to a Different Modality	5 (14.7%)	5 (14.7%)
Interacting with Medical Professionals	5 (14.7%)	2 (5.9%)
Measuring Accessibility In The Wild	3 (8.8%)	1 (2.9%)
Making Comparisons	3 (8.8%)	1 (2.9%)
Characterizing Accessibility Needs	2 (5.9%)	1 (2.9%)

TABLE III
FREQUENCY OF CODES IN *issues addressed*. 'THIS CODE ONLY' COUNTS INSTANCES WHERE THE CODE WAS APPLIED IN ISOLATION, NOT ALONGSIDE ANY OTHER CODES IN THIS DIMENSION.

3) Contribution Type: We added a *contribution type* dimension to our taxonomy to capture a common theme across visualization [5], HCI [41], and accessibility research [11]. This classification is based on the research contribution types in HCI outlined by Wobbrock et al [41]. Among the seven types they identified - artifact, methodological, empirical, theoretical, dataset, survey, and opinion - our review found examples of all except for the *opinion* contribution. In addition, we recognized the need for an additional category to adequately represent the breadth of visualization research. Consequently, we expanded our classification to include *algorithm* as a distinct contribution type, resulting in seven contribution types throughout our taxonomy.

Our findings revealed diverse contributions, where artifact contributions were the most popular at 76.5% (N=26). Other contribution types included empirical (8.8%, N=3), theoretical (8.8%, N=3), dataset (2.9%, N=1), algorithm (8.8%, N=3), survey (2.9%, N=1), and methodological (2.9%, N=1). The prevalence of artifact contributions in our corpus (76.5%, N=26) underscores a significant emphasis on developing tangible tools and solutions within the field. In contrast, the relatively low occurrence of empirical contributions (8.8%, N=3) markedly differs from the broader trend in accessibility literature, where empirical contributions typically dominate [11]. This discrepancy highlights a clear gap in the empirical validation of novel techniques and methodologies, a crucial aspect typically emphasized in broader accessibility research [11].

Although survey (2.9%, N=1), dataset (2.9%, N=1), and methodological (2.9%, N=1) contributions were less frequent in our study, this scarcity aligns with the similar trends observed in accessibility research [11]. Therefore, their limited representation in our findings does not imply they are less important but rather reflects broader patterns in accessibility research.

B. Research Methodology

1) Study Methods: We incorporated *study methods* as a dimension to identify the user-centric approaches in accessible data representation research. This dimension's codes are based on methods commonly used in both accessibility [11] and HCI research [52]. Our aim was to investigate how researchers engage and prioritize users with disabilities, specifically when creating new accessible data representations.

Our review identified ten methods within our corpus, emphasizing the importance of categorizing these to understand how users with disabilities are integrated into research practices. This is crucial in accessibility contexts, where understanding user needs and abilities is vital [12].

Our findings reveal a diverse range of research methods, with controlled experiments (29.4%, N=10) and interviews (23.5%, N=8) being the most prevalent. Case studies and prototyping were also notable, each accounting for 14.71%(N=5). Only 26.5% (N=9) of the 34 papers utilized more than one research method. However, methodologies like usability testing, which are crucial for assessing accessible technologies [52], were less frequently used (8.8%, N=3). Additionally, as shown in Table IV, other standard research methods in user studies, such as design workshops (11.76%, N=4), focus groups (2.94%, N=1), and field studies (5.88%, N=2), appeared less often in our analysis. These observations correlate with our earlier findings regarding the limited empirical contributions.

Contrary to the expectations of human-centered design that prevail in HCI and accessibility research [11], [42], only 64.7% (n=22) of the 34 papers incorporated user studies. Among the twelve papers that did *not* include user studies, the employed research methods encompassed algorithm and system analyses (e.g., [38], [53]), surveying the accessibility of interactive data visualizations (e.g., [46]) and the development of assistive technology prototypes without subsequent user evaluations (e.g., [49], [54]). These methods undoubtedly contribute to the field, but the absence of user studies, whether for initial development or subsequent evaluation, limits the incorporation of valuable insights and perspectives from the disability communities targeted. Relying solely on literature or theoretical frameworks for creating and evaluating accessible technology is insufficient [52]. Additionally, this approach hinders our ability to gauge the real-world effectiveness of new accessible data representations, specifically regarding their actual benefits for users with disabilities.

Study Methods	Papers w/ Code	This Code Only
Controlled Experiments	10 (29.4%)	8 (23.5%)
Interviews	8 (23.5%)	3 (8.8%)
Case Studies	5 (14.7%)	2 (5.9%)
Prototyping	5 (14.7%)	5 (14.7%)
Workshop/Design	4 (11.76%)	1 (2.9%)
Survey	3 (8.82%)	1 (2.9%)
Usability Studies	3 (8.8%)	1 (2.9%)
Other	3 (8.8%)	3 (8.8%)
Field Study	2 (5.88%)	1 (2.9%)
Focus Groups	1 (2.9%)	0 (0.0%)

TABLE IV
FREQUENCY OF CODES IN *study methods*. 'THIS CODE ONLY' COUNTS INSTANCES WHERE THE CODE WAS APPLIED IN ISOLATION, NOT ALONGSIDE ANY OTHER CODES IN THIS DIMENSION.

2) Participants Involved: Understanding *who* participates in research is as essential as understanding *what* is being researched. Central to accessibility research is the involvement of users with disabilities, whose insights are important in developing effective solutions. This dimension evaluates the extent to which studies in our dataset have integrated these critical perspectives. Our analysis not only focused on the presence of user studies but also scrutinized the specific user groups involved. Adopting the participant categorization used by Mack et al. [11], we ensured our analysis aligned with established norms in accessibility research.

Our classification schema, designed in alignment with accessibility research [11], allowed us to identify five participant types in these studies: people with disabilities, older adults, people without disabilities, specialists, and caregivers. It is crucial to acknowledge that these categories often intersect; for instance, a specialist or caregiver may also be a person with or without a disability. However, in our classification, *people without disabilities* specifically refers to the general population not identified with disabilities. This category excludes those identified primarily by their roles, such as specialists or caregivers. Therefore, if the primary focus in a study was on individuals in their capacity as specialists or caregivers, regardless of their disability status, we classified them under their specific roles.

Of the 22 papers incorporating user studies, as illustrated in Table V shows that the majority (63.6%, n=14/22) featured participants with disabilities and older adults. Among the eight papers that did not involve these demographics, 37.5% (n=3/8) included participants who were either specialists or caregivers. Additionally, six papers presented a mix of participants, combining individuals with disabilities or older adults with those without disabilities, specialists or caregivers.

Recruitment of users for accessibility research can prove challenging due to the limited number of representatives and the difficulties in locating suitable users [55]. So, we analyzed the number of participants reported in the 22 papers that conducted user studies. The median number of participants was 7 (M=19.8, SD=33.5). Upon closely reviewing papers that conducted user studies exclusively with participants who either have disabilities or are older adults, we found that these studies typically had smaller sample sizes with a median sample size of 5.5 (M=7.6, SD=7.2). Among these, seven out of the eight papers had sample sizes of fewer than ten participants.

C. Data Representation

1) Data Type: Based on Shneiderman's data type classification [40], we categorized the data in our corpus into five types, aligning with visualization research. Additionally, we introduced a sixth category, *non-specific*, to account for instances where researchers did not focus on a specific data type. This expansion ensures our categorization comprehensively represents all data types encountered in our analysis.

Our review revealed a diverse utilization of data types. Two-dimensional data types, which traditionally represent maps and planar data, were featured in

Participants Involved	Papers w/ Code`	This Code Only
People with Disabilities	11 (50.0%)	7 (31.8%)
Specialist	8 (36.4%)	3 (13.6%)
People without Disabilities	7 (31.8%)	5 (22.7%)
Older Adult	3 (13.6%)	1 (4.5%)
Caregiver	1 (4.5%)	1 (4.5%)

TABLE V
THE FREQUENCY OF APPLIED CODES FOR *participants involved*. THIS ANALYSIS IS EXCLUSIVELY BASED ON PAPERS INCORPORATING USER STUDIES, WITH A TOTAL SAMPLE SIZE OF N=22.

nearly half (47.06%, N=16) of the papers within our review, followed by multidimensional data, which was present in 32.35% (N=11) of the papers. Although less frequent, one-dimensional (14.71%, N=5), temporal (17.65%, N=6), and tree (8.82%, N=3) data types were also identified in our analysis—see Figure 3. We discovered that seven papers utilized multiple data types. Interestingly, we observed that multiple data types were often used in conjunction, especially temporal data, which rarely appeared in isolation. Three papers, all of which aimed at devising frameworks, did not focus on presenting a specific data type, were classified as non-specific, underscoring the versatility and broad applicability of these frameworks for various data types (e.g., [30], [43], [56]).

2) Visualization Type: We analyzed visual encodings in our corpus to better understand the diverse representations utilized to present data to people with disabilities. Unlike other visualization surveys that often group various visualization types (such as basic versus advanced charts) [4], [57], we chose to maintain detailed distinctions of the specific visualization types employed by researchers. This allowed us to precisely identify which visualizations have been modified for accessibility and those used to depict elements related to access.

We identified eleven types of visualizations utilized for accessible data representations. Maps emerged as the most prevalent visualization type in our analysis, constituting 38.2% (N=13) of the papers, as shown in Table VI. This prevalence underscores the critical role of spatial data in enhancing accessibility and navigating physical spaces. In cases where authors were not specific about the visualization type or suggested that their work could be generalized across various types, we classified these instances as *general graphics*. This category was identified in 20.6% (N=7) of our corpus, capturing a broad spectrum of papers. Line charts and bar charts, each accounting for 14.7% (N=5) of the visualizations, also demonstrate their enduring popularity. Less frequently, we encountered instances of pie charts (2.9%, N=1), glyphs (8.8%, N=3), tables (2.9%, N=1), treemaps (5.9%, N=2), bubble charts (2.9%, N=1), boxplots (2.9%, N=1), and textual visualizations (8.8%, N=3). We included *textual visualizations* in our classification to illustrate how words and sounds can be effectively represented as data through visual encodings that incorporate actual text. This category highlights the use of textual elements, like word clouds (e.g., [8]) or captions (e.g., [51]), as a means to represent auditory or linguistic data visually. This type of visualization is especially effective for the DHH community, where visual representation significantly enhances data accessibility.

Our analysis identified the most commonly used visualization types and highlights innovative applications, such as employing textual visualizations in online meetings to aid DHH individuals, exemplified by the work of Iijima et al. [8]. This instance shows how traditional visualizations can be adapted to make otherwise inaccessible data available to diverse audiences. Furthermore, our findings reveal the potential for creatively adapting existing visual representations to enhance data accessibility.

Visualization Type	Papers w/ Code`	This Code Only
Maps	13 (38.2%)	13 (38.2%)
General Graphics	7 (20.6%)	7 (20.6%)
Line Chart	5 (14.7%)	2 (5.9%)
Bar Chart	5 (14.7%)	2 (5.9%)
Glyph	3 (8.8%)	1 (2.9%)
Textual	3 (8.8%)	3 (8.8%)
Treemap	2 (5.9%)	0 (0.0%)
Pie Chart	1 (2.9%)	1 (2.9%)
Tables	1 (2.9%)	0 (0.0%)
Bubble Chart	1 (2.9%)	1 (2.9%)
Boxplot	1 (2.9%)	0 (0.0%)

TABLE VI
FREQUENCY OF CODES IN *visualization types*. 'THIS CODE ONLY' COUNTS INSTANCES WHERE THE CODE WAS APPLIED IN ISOLATION, NOT ALONGSIDE OTHER CODES IN THIS DIMENSION.

3) Data Domain: We classified data domains to shed light on the diverse contexts and objectives behind crafting accessible data representations. This classification is consistent with approaches seen in other visualization surveys [57], offering valuable insights into the usual environments and applications from which data for these visualizations is sourced. We identified five key domains – navigation, wellbeing/health, sound, education, and general – each offering unique insights into where and how accessible data representations are needed and currently applied.

Understanding the source domains of data is crucial in identifying the goals and challenges of accessibility. Navigation, primarily concerned with spatial data and movement within spaces, is vital for physical accessibility studies. Wellbeing/Health focuses on improving various health outcomes, while papers in the sound domain address the accessibility of auditory information.

Similarly, education plays a crucial role in ensuring the accessibility of learning materials and environments. Meanwhile, the general category encompasses studies spanning multiple domains or those not aligning with a specific domain.

Our analysis revealed that the most familiar domain was navigation (38.2%, N=13), which includes papers that focus on accessible data for tasks such as navigation (e.g., [58]), wayfinding (e.g., [59]), assisting people using public transportation (e.g., [60]), and provide people with motor impairments to practice navigating maps through a virtual simulator [61]. This prevalence highlights the potential for enriching visual representations with access-related details—such as information on sidewalk conditions or transit accessibility. Moreover, the wellbeing/health domain also emerged as prominent (20.6%, N=7),focusing on areas such as personal health data communication (e.g., [62]), support for physical therapy patients (e.g., [63]), and improved interactions with healthcare providers (e.g., [64]). Other domains like education and sound were less represented, each accounting for 8.8% (N=3) of the studies. Additionally, a general category, encompassing studies across multiple domains or those not fitting into a specific category, represented 23.5% (N=8) of the papers."

The relative scarcity of education-focused papers is particularly notable, given the increasing emphasis on accessibility in STEM visualizations for students with disabilities. Research efforts in this domain serve various objectives. Some studies aim to develop guidelines for making educational materials more accessible (e.g., [43], [65]). In contrast, others employ data visualization dashboards to understand better the behavior of students with learning disabilities (e.g., [66]). Moreover, the substantial presence of studies in the general domain underscores the need for more domain-specific research, which could enhance our understanding of accessible data in varied contexts.

VI. Discussion

In recent years, visualization, HCI, and accessibility have seen significant growth in research focusing on accessible data representations [5]. However, this increase has not necessarily translated into a deeper, more nuanced understanding of the diverse needs across different disability communities. Our analysis seeks to fill this gap by expanding the traditionally narrow focus of accessible data representations, predominantly centered on the BLV community [3], [4]. To achieve this broader perspective, we introduce a new scope for what should be included in accessible data representation research. In addition to identifying novel opportunities for accessible data representations for various disabilities, we offer a preliminary framework. This initial guide is intended to assist future researchers in understanding and exploring ways to integrate accessibility into the data visualization design process. With these contributions, we aim to pave the way for a more comprehensive and inclusive discourse on data accessibility.

A. Expanding The Scope of Accessible Data Representations

Unsurprisingly, the focus has been on individuals with visual impairments, given the inherent association of "visualization" with vision impairment. Notably, authors in accessible data visualization research commonly allude to the argument that visualizations are fundamentally constructed based on the principles of the human visual system (e.g., [4], [67]), thereby underscoring the perceived significance of catering to the needs of individuals with visual impairments. While this focus is understandable, it limits the field's potential for broader impact. It is worth noting that the ultimate goal of data visualization is not solely to present data visually but to facilitate data-driven insights [34], [68]. However, these insights can manifest through various formats, including auditory, tactile, or interactive representations.

To shift conventional mindsets around accessible visualization, we recommend a more inclusive term: *data representations*. This term is beneficial for expanding the scope of accessibility discussions, as it acknowledges that conveying data-driven insights can happen through multiple modalities, not just visual ones. Although the broader field of data visualization may continue prioritizing visual representations, within the accessibility subdomain, a broader set of techniques is increasingly necessary. Data representations can support auditory and tactile modalities and include representations employing innovative interaction techniques [33]. By adopting this more encompassing terminology, we can better encapsulate the diversity and inclusivity needed to advance data accessibility.

In examining the current landscape of accessible data representation, we observed a predominant focus on translating visual data to accommodate different modalities. Specifically, much of the existing research centers on converting visualizations to auditory [22], or tactile [69] formats or enhancing their compatibility with screen reader technology [70]. While these are critical advancements for fostering equity in data accessibility, our analysis uncovers additional dimensions of the issue. We found that even visual representations, potentially beneficial for individuals with non-visual disabilities, may remain inaccessible. This inaccessibility arises from factors such as inadequate interaction design for those with motor impairments or older adults [33], [62], insufficient support for neurodivergent individuals [35], or the lack of accessible information in the visual representations [48], [71], limiting informed decision-making for people with disabilities. Thus, a comprehensive approach to the study of accessible data representations should not

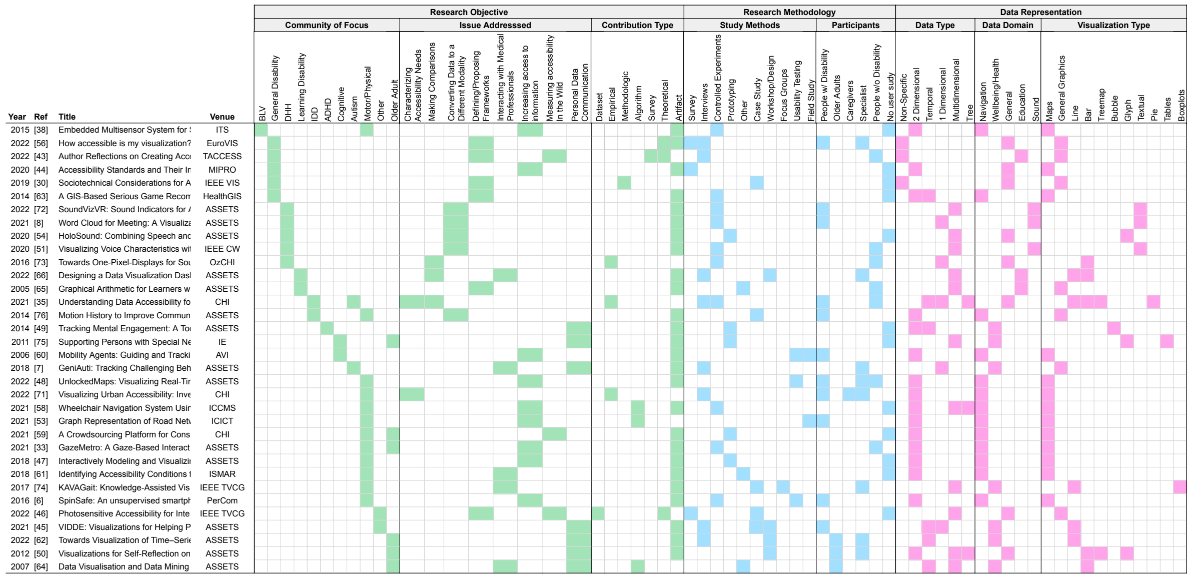

Fig. 3. From our total corpus of 152 papers, we selected 34 papers that focus on non-visual accessibility. This figure organizes our eight dimensions into three main categories: Research Objective, Research Methodology, and Data Representation, showing the coding scheme applied to each paper.

only aim to make visual data more accessible but should also address these multidimensional challenges.

By redefining the scope of accessible data representations, we can move beyond the limited focus on visual accessibility. We advocate for a broader approach that includes various representations, guidelines, and interactions designed to meet the diverse needs of different user groups. However, while building upon the existing strengths of the visualization community, we recommend expanding its scope to consider a multiplicity of modalities, channels, and senses and to embrace interdisciplinary methodologies. Importantly, we also see a pressing need for increased cross-community collaboration [4] to ensure that progress in accessible data research is not hindered. This multidisciplinary and collaborative approach enables us to cater to a more diverse range of user needs and abilities, pushing the boundaries of what accessible data representations can achieve.

B. Opportunities and Challenges

Informed by our systematic literature review and expanded perspective on accessible data representation, we delineate the following avenues for future exploration:

Incorporating a Wider Range of Access-Related Elements in Data Representations: Data representations pervade a variety of domains, such as education, health, and navigation, and they are often rigorously tested prior to deployment to optimize how information is conveyed. While numerous frameworks and guidelines exist for effective data display, they often fail to address the specific requirements for displaying access-related data. The issue is not necessarily the need for entirely new representations but rather an expansion of current ones to include more access-related elements [3]. These access-related elements, which facilitate better physical-world access, may encompass a variety of factors such as sidewalk conditions [47], transit accessibility [48], and auditory cues [72]. For example, although data representations related to navigation can provide crucial information about route accessibility for individuals with motor impairments, there is limited research on the best methods for integrating these elements into established two-dimensional representations. Similarly, sound information visualization aims to use visual aids to convey auditory data. To better assist individuals who are deaf or hard-of-hearing, these visual representations could be enhanced by including locational data that indicates the source of the auditory information. Despite some attempts to incorporate these access-related elements into data representations [44], a standardized framework for their inclusion remains conspicuously absent, limiting their utility for people with disabilities in making informed decisions.

Utilizing Data Visualizations as an Accessible Data Representation: As previously noted, the scope of data representations has broadened considerably; it is no longer confined to mere visual representations. Data visualizations emerged as powerful tools for making data more comprehensible and accessible to the general populace. Over time, these visualizations have also evolved to address the accessibility needs of people with diverse impairments. In our refined dataset of 34 papers, every study included visual elements in creating accessible data representations for individuals with non-vision impairments, underscoring the significance visual representations still have in accessible data representations. For instance, our review identified innovative uses of sound information visualizations through one-pixel displays [73] and the employment of word clouds in virtual meetings to assist those with hearing impairments [8]. Additionally, data visualizations have been strategically utilized to support individuals with dyscalculia [65]—a learning disability that affects mathematical abilities.

Our findings reveal the types of data used in these papers, categorized according to traditional visualization data types such as 1-dimensional, 2-dimensional, tree structures, and others. This classification underscores the idea that these alternative forms of data representation are, at their core, still rooted in principles of effective data visualization. Future studies must first identify the specific type of data they aim to make accessible. Once the data type is determined, researchers can then assess whether data visualizations serve as an effective medium for conveying this information. Knowing the data type will also enable researchers to draw upon established best practices from data visualization as a foundational starting point for making data more accessible.

Embracing Diversity in Accessible Data Representation Design: Recognizing the diversity of needs within disability communities is crucial for advancing the field of accessible data representation. The heterogeneity principle within disability communities necessitates a nuanced approach, as a one-size-fits-all model is often infeasible even within a single disability community. For instance, the varied manifestations of motor disabilities call for universally accessible data interactions [33], [74]. While numerous data representation guidelines have origins in cognitive sciences, these are principally tailored to neurotypical populations. Wu et al. contend that new guidelines catering to the unique information processing needs of neurodiverse populations, such as those with IDD, must be developed to facilitate sense-making and decision-making tasks effectively [34], [35]. Such observations lead to a pivotal consideration: the inherent limitations of Universal Design (UD) for data representations. While UD strives for comprehensive accessibility, it often falls short of meeting the intricate and unique requirements of diverse disability communities. An alternative approach, ability-based design [12], aims to optimize data representation by capitalizing on the specific abilities of individual users. This realization underscores the need for a paradigmatic shift in research focus—from merely identifying inaccessible elements in data representations to actively iterating design adjustments that accommodate various cognitive needs.

Our review found numerous instances where research contributions targeted multiple disability communities [33], [35], [38], [59], [75], [76]. Despite the apparent complexity in addressing the heterogeneity of disabilities, various accessibility frameworks have demonstrated utility across multiple disability communities [11], [43], [56]. Nevertheless, in alignment with established accessibility practices [11], [42], we caution against overly generalizing disability categories. Although research on accessibility for conditions like photosensitive epilepsy [46] and chronic obstructive pulmonary disease (COPD) [45], [77] remains in its infancy [11], they can be an additional avenue for exploration in creating accessible data representations.

Utilizing Alternative Inputs to Interact with Data Representations: The scope of accessible data representations is not limited to diversifying how data can be consumed; it also includes how users interact with these representations through various input modalities. Traditional data representations often presuppose specific sensory and motor capabilities [4], creating accessibility barriers. Although substantial research exists on diverse input modalities in broader fields like virtual reality [78], social media navigation [79], and interactive public displays [80], the subject of alternative input modalities specifically for interacting with data representations has received less attention [3].

In our survey, only a few instances were identified where alternative input modalities—apart from touch—were employed to facilitate interaction for users with disabilities. These were gaze-based input [33] and voice-activated conversational user interfaces [62]. This limited focus is particularly noteworthy given the expanding research landscape in accessible technology, where gaze-based [81] and voice-activated inputs [82] have gained prominence.

The potential for enhancing accessible data representations through alternative input modalities is further highlighted by research targeting the BLV community [5], [21]. For instance, Sharif et al. integrated voice-activated commands for screen reader users to explore additional information about a data visualization [70]. Future research should explore and integrate alternative input modalities, broadening the interaction possibilities within data representations.

Advocating User-Centric Methodologies: The role of user abilities in shaping interactions with technology is a well-established principle within the HCI domain. The necessity for including representative users in usability studies and controlled experiments gains heightened significance in accessibility research. This is particularly the case when the target user population possesses unique abilities or experiences that influence their approach to tasks [55]. Previous work has shown that research focusing on non-representative users can yield inaccurate conclusions or overlook valuable insights [83]. Consequently, we assert that adopting user-centric methodologies is imperative for developing genuinely accessible data representations.

Although it's positive that about half of the papers in our refined dataset involved participants with disabilities, there is still potential for further improvement. Specifically, several prototypes and systems were not designed for or evaluated by their intended end users. Although proxies and theoretical models can offer valuable insights, they are not substitutes for the lived experiences of individuals with disabilities [52]. We suggest that future research could benefit from adopting participatory and co-design approaches, which have been recognized as effective methodologies in developing inclusive solutions [11], [18].

Expanding Personal Data Visualization for Disability Inclusion: The increasing prevalence of personal data visualizations reflects the growing role of data in modern life [1]. However, there is a notable gap in applying these visualizations to enhance the quality of life for individuals with disabilities. Our survey shows that a portion of work on accessible data representation—particularly as it pertains to older adults—focuses on the effective communication of personal information (e.g., [50], [62], [64], [75]). For example, intelligent medication blisters and task-based calendars have been shown to empower older adults with greater autonomy [75]. Moreover, Jones et al. demonstrated the efficacy of these data representations in facilitating older adults' understanding of their behaviors [50].

Additionally, Chen et al. offer compelling evidence of personalized data representations' impact on individuals with specific conditions, such as COPD [45]. Their study emphasized the effectiveness of tailoring visual data representations to offer essential insights and reassurance during physical activities for individuals managing chronic illnesses. While the advantages of personal data visualizations are clear [1], our findings suggest that effectively personalizing data representations for individuals with disabilities involves collaborating with these communities. It is essential to understand which data is most relevant to them and how they can benefit from this data being presented in a way that facilitates learning or insight generation about themselves. Future research should aim to identify the specific types of personal data that are most valuable for decision-making within disability communities. This approach is vital, as their needs and preferences may vary from the conventional norms of personalization.

C. Preliminary Framework for Creating Accessible Data Representations

As we navigate these challenges and opportunities, there is a pressing need to embed accessibility into every stage of the data representation design process. Our preliminary framework refines the standard data visualization design process with a strong emphasis on accessibility. Contrasting with existing models [5], [84] that often retrofit visualizations for accessibility post-design, we advocate for accessible data representations to be inherently inclusive from the start.

1) Inclusive User Characterization: In designing data representations for communities with disabilities, we prioritize ability-based design [12], focusing on the unique needs of these communities. This requires understanding the abilities and barriers users face, especially those with cognitive or motor disabilities who are often overlooked in visualization research [4]. By considering various sensory, cognitive, and motor abilities, our designs become more accessible and inclusive. This approach is crucial for addressing gaps in our taxonomy, particularly among neurodiverse communities (e.g., Learning Disabilities, IDD, ADHD, Cognitive Impairments, Autism), which have been underrepresented despite their diverse cognitive abilities. Current visualization guidelines, primarily based on empirical studies focused on perception and cognition in neurotypical users, might not adequately cater to the information processing needs of neurodiverse individuals. Acknowledging and taking an ability-based approach to address the distinct cognitive abilities within different communities is essential.

Moreover, data representation research should include a more diverse range of participants, including those with disabilities, to uncover previously unexplored cognitive abilities. This diversity is critical to making data representations more inclusive and ensures that our design guidelines (e.g., [85], [86]), transcend assumptions rooted in non-disabled, neurotypical user experiences. Such an inclusive approach leads to more equitable and universally accessible data practices.

2) Identifying Accessibility-Related Data: Here, we emphasize integrating accessibility-related data into existing representations to serve people with disabilities better. Our review identified several adaptations to typical data representations to accommodate the needs of people with disabilities. For example, adding details about accessible features (e.g., ramps, in-service elevators) in maps could significantly aid those with motor disabilities in navigating the physical world [48], [58]. Similarly, tailoring data visualizations to track and manage complex behavioral data of autistic children has been effective for caregivers [7].

This step aims to evolve standard data representations into more inclusive tools, displaying data that matters most to disability communities. This approach aligns with our taxonomy's findings, where there is a need for more tailored data representations in domains like health and education for various disability communities. By focusing on relevant data for these communities, we ensure that data representations are not just accessible but also meaningful, supporting users with disabilities in understanding their environment and needs — aligning with the fundamental purpose of data visualizations [68].

3) Encoding Accessible Data Representations: This stage highlights the need for encoding data in multiple modalities — visual, auditory, and tactile — to address the lack of diversity in current visualization types. Our taxonomy demonstrates that accessible data representations rely on maps, general graphics, line charts, and bar charts. Researchers should adopt multimodal approaches to overcome this to develop novel, accessible representations for underutilized visualizations like treemaps, bubble charts, glyphs, and other advanced visualizations. Creating accessible representations of these visualizations can enable more inclusive and richer data experiences.

Furthermore, designing accessible data representations involves considering diverse input methods for data interaction. As highlighted in our review, research in this domain is currently limited, with a few examples like gaze-based interactions for motor disabilities [33] and voice interfaces for older adults [62]. Our analysis found no examples of interactive visualizations as accessible data representations. While research focuses on making visual data accessible by converting it to different modalities, there is also significant potential to improve accessibility by offering new ways for users to interact with visual data. Emphasizing the need for a broader spectrum of input modalities, we can enhance data interaction accessibility for individuals with different cognitive and physical abilities and transform static visualizations into dynamic, interactive experiences through accessible designs.

4) Building and Evaluating Accessible Data Representations: The final phase focuses on user testing, especially involving individuals from disability communities. The goal is to ensure that data representations are practical and accessible in real-world settings. Our taxonomy reveals a lack of traditional accessibility research methods like design workshops, focus groups, usability testing, and field studies. Addressing this, we advocate for incorporating these user-centered approaches, which are vital for verifying that data representations effectively meet the diverse needs of users with disabilities.

Incorporating these methods into our framework not only addresses specific challenges in accessible data representation but also enriches empirical contributions in this field, which our taxonomy indicates is currently lacking despite the broader patterns in accessibility research [11]. By engaging directly with users with disabilities in these research methods, we can gain valuable insights and feedback, leading to more inclusive and effective data representation designs.

D. Bridging the Gap: Insights from BLV-Focused Accessible Data Research

Accessible data representation research encompasses the distinct needs of diverse disability groups, including older adults and those with motor, physical, visual, cognitive, and auditory disabilities. However, the research has disproportionately focused on the BLV community. Although we did not profoundly analyze papers dedicated exclusively to the BLV community, due to existing surveys [5], we will discuss the promising opportunities it presents.

A key lesson gleaned from BLV research is the essential role of multimodal interactions in data representation [24], [87]–[94]. The range of these methods is vast, extending from auditory encoding techniques, such as textual descriptions conveyed through speech [91], [95]–[97], to sonification, the use of non-speech sounds [42], [91], [98]–[101]. Other methods involve advanced haptic feedback systems [87], [88], [102], and physicalization for tactile representations [69], [89], [103]–[107].

This diverse set of representations does more than offer alternatives for data interaction—they enrich the overall user experience by making it more engaging. A multimodal approach can benefit various disabilities, mainly auditory and motor/physical, where these alternative modalities can effectively supplement or even substitute traditional visual representations.

Another pivotal insight from BLV research is the importance of rigorous experimentation when evaluating the accuracy and usability of alternative data representations. Researchers in this field conduct thorough empirical studies, often employing quantitative and qualitative methods to validate their proposed solutions [70], [108], [109]. This process typically involves tasks designed to evaluate how effectively participants can understand and use the data representations, often examining their accuracy, speed, and satisfaction in performing these tasks [70], [108], [109].

These rigorous testing approaches provide valuable insights into the strengths and limitations of different design solutions, guiding subsequent refinements. The adoption of such robust methodologies can prove advantageous across various disability categories. Independent of the disability type, robust empirical validation can ensure the development of tools that not only meet accessibility requirements but also provide a positive and efficient user experience [94], [110]–[112]. By recognizing the value of these meticulous experimental methodologies, researchers in accessible data representation can contribute to creating more effective and usable solutions for all types of disabilities.

BLV research emphasizes the importance of user-centered design in evaluating accessible data representations. This involves incorporating users from the target community in the design process, from conception to evaluation [21], [113]. This approach offers invaluable insights into the unique needs, preferences, and experiences of different disability groups, leading to more relevant and practical design solutions. For example, leveraging user-centered design in cognitive disabilities research could lead to a better understanding and accommodation of this group's varied information-processing abilities.

Research on data representations for the BLV community spans various data domains, offering valuable insights for other disability groups. Given the prevalence of navigation and wayfinding in our findings, it is worth considering that these challenges are not exclusive to just one disability community. Solutions such as tactile/haptic maps [114]–[116], auditory navigation aids [44], [114], [117], or safety navigation tools [118], initially developed to increase access to the physical world for BLV individuals, could guide the design of accessible data representations for people with motor or physical disabilities, as well as older adults. The extensive research on access-related features in spatial data representations for the BLV community can serve as a foundation for adapting these solutions to meet the unique navigational needs of individuals with other types of disabilities.

Similarly, within education, numerous accessible data representations tailored to the BLV community, such as accessible diagrams [97], [119], [120], generating textual descriptions [121], or auditory graphs for STEM courses [122], have been developed to facilitate learning [69], [104]. In one instance from our 34-paper corpus, we found where data representations were explored to support math skills in students with learning disabilities [65]. However, these existing solutions could also serve as inspiration for accessible data representations for learners with cognitive impairments and learning disabilities, emphasizing the need to explore alternative representations like textual descriptions and accessible diagrams to cater to their specific needs.

Expanding upon the role accessible data representation serves in various domains, the BLV community has seen the development of accessible data representations that support health information [123] and navigation through health facilities [124]. These advances in health-related data representation for the BLV community can serve as a foundational model for developing similar tools tailored for individuals with non-vision impairments. For instance, identical to how Sharif et al. [48] used real-time accessibility data to help people navigate through transit stations, data representations that include specific accessibility features could assist individuals with motor impairments in finding accessible routes through complex healthcare facilities. By extending these innovations to other disability communities, we can enhance health literacy and empower individuals to manage their well-being.

Although the focus of accessible data representations is primarily on the BLV community, the insights from this research can serve as a vital source of inspiration and knowledge. These insights can guide the design and development of effective and accessible data representations for various disability groups, irrespective of the specific disability in focus.

VII. Limitations

Our study provides an extensive analysis but is limited in certain aspects. First, we focused our literature search on IEEE Xplore, ACM Digital Library, and select academic venues. This decision, while leveraging reputable sources, potentially overlooks contributions from interdisciplinary fields such as special education, mechanical engineering, and cognitive psychology. This limitation may affect the depth and diversity of perspectives in our review.

Additionally, our research specifically targeted papers that utilize data visualization principles, aiming to highlight the emerging trend in accessible data representations. This focus was particularly chosen to address the lack of attention towards non-vision impairments in Human-Computer Interaction (HCI). While this approach helped us uncover unique challenges and opportunities in this area, it also means that other data-driven interventions for various disabilities, which might not primarily focus on displaying a data repreentation, were not included in our study.

VIII. Conclusion

This systematic review has comprehensively examined the current landscape of accessible data representation research, focusing on understanding data accessibility across all disabilities. Our initial investigation indicated a strong focus on research aimed at the BLV community. However, our subsequent analysis has shown that accessible data representations can benefit a broader spectrum of disabilities and should be developed with this diversity in mind.

Our study emphasized the importance of adopting a more inclusive approach to accessible data representations, which entails developing and implementing diverse representations that cater to the unique needs of various user groups. By doing so, we can ensure that individuals with different abilities and requirements can effectively engage with and derive meaningful insights from data. Furthermore, our findings serve as a clarion call for researchers and practitioners alike to actively pursue the development of novel methodologies and representations that foster greater accessibility, inclusivity, and adaptability in data representations.

As we move forward, it is imperative to continue refining and expanding our understanding of accessible data representations across all disabilities while promoting the development of innovative solutions that address the diverse needs of this rapidly evolving field. By embracing this holistic approach, we will be better positioned to make significant strides in bridging the accessibility gap and empowering individuals with disabilities to participate fully in the digital age. We hope this systematic review will inspire further research and collaboration, ultimately paving the way for a more inclusive and accessible future for all.

References

[1] D. Huang, M. Tory, B. A. Aseniero, L. Bartram, S. Bateman, S. Carpendale, A. Tang, and R. Woodbury, "Personal visualization and personal visual analytics," IEEE Transactions on Visualization and Computer Graphics, vol. 21, no. 3, pp. 420–433, 2014.

[2] A. Wolff, D. Gooch, J. J. C. Montaner, U. Rashid, and G. Kortuem, "Creating an understanding of data literacy for a data-driven society," The Journal of Community Informatics, vol. 12, no. 3, 2016.

[3] B. Lee, E. K. Choe, P. Isenberg, K. Marriott, and J. Stasko, "Reaching broader audiences with data visualization," IEEE Computer Graphics and Applications, vol. 40, no. 2, pp. 82–90, 2020.

[4] K. Marriott, B. Lee, M. Butler, E. Cutrell, K. Ellis, C. Goncu, M. Hearst, K. McCoy, and D. A. Szafir, "Inclusive data visualization for people with disabilities: A call to action," Interactions, vol. 28, no. 3, p. 47–51, apr 2021. [Online]. Available: https://doi.org/10.1145/3457875

[5] N. W. Kim, S. C. Joyner, A. Riegelhuth, and Y. Kim, "Accessible visualization: Design space, opportunities, and challenges," in Computer Graphics Forum, vol. 40, no. 3. Wiley Online Library, 2021, pp. 173–188.

[6] F. Seraj, P. J. M. Havinga, and N. Meratnia, "Spinsafe: An unsupervised smartphone-based wheelchair path monitoring system," in 2016 IEEE International Conference on Pervasive Computing and Communication Workshops (PerCom Workshops), 2016, pp. 1–6.

[7] K. Choi, D. Jang, D. Lee, and S. Park, "Geniauti: Tracking challenging behaviors of children with autism for data-driven interventions," in Proceedings of the 20th International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '18. New York, NY, USA: Association for Computing Machinery, 2018, p. 480–482. [Online]. Available: https://doi.org/10.1145/3234695.3240987

[8] R. Iijima, A. Shitara, S. Sarcar, and Y. Ochiai, "Word cloud for meeting: A visualization system for dhh people in online meetings," in Proceedings of the 23rd International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '21. New York, NY, USA: Association for Computing Machinery, 2021. [Online]. Available: https://doi.org/10.1145/3441852.3476547

[9] M. Butler, L. M. Holloway, S. Reinders, C. Goncu, and K. Marriott, "Technology developments in touch-based accessible graphics: A systematic review of research 2010-2020," in Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, ser. CHI '21. New York, NY, USA: Association for Computing Machinery, 2021. [Online]. Available: https://doi.org/10.1145/3411764.3445207

[10] (2023, Mar) Disability. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/disability-and-health

[11] K. Mack, E. McDonnell, D. Jain, L. Lu Wang, J. E. Froehlich, and L. Findlater, "What do we mean by "accessibility research"? a literature survey of accessibility papers in chi and assets from 1994 to 2019," in Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, ser. CHI '21. New York, NY, USA: Association for Computing Machinery, 2021. [Online]. Available: https://doi.org/10.1145/3411764.3445412

[12] J. O. Wobbrock, S. K. Kane, K. Z. Gajos, S. Harada, and J. Froehlich, "Ability-based design: Concept, principles and examples," ACM Trans. Access. Comput., vol. 3, no. 3, apr 2011. [Online]. Available: https://doi.org/10.1145/1952383.1952384

[13] "Web content accessibility guidelines (wcag) 2.1." [Online]. Available: https://www.w3.org/TR/WCAG21/

[14] S. Oviatt, T. Darrell, and M. Flickner, "Multimodal interfaces that flex adapt, and persist." Communications of the ACM, vol. 47, no. 1, pp. 30–33, 2004.

[15] Z. Obrenovic, J. Abascal, and D. Starcevic, "Universal accessibility as a multimodal design issue," Communications of the ACM, vol. 50, no. 5, pp. 83–88, 2007.

[16] A. M. Cook and J. M. Polgar, Assistive technologies-e-book: principles and practice. Elsevier Health Sciences, 2014.

[17] V. Koushik and S. K. Kane, "Towards augmented reality coaching for daily routines: Participatory design with individuals with cognitive disabilities and their caregivers," Int. J. Hum.-Comput. Stud., vol. 165, no. C, sep 2022. [Online]. Available: https://doi.org/10.1016/j.ijhcs.2022.102862

[18] C. Quintero, "A review: accessible technology through participatory design," Disability and Rehabilitation: Assistive Technology, vol. 17, pp. 1–7, 07 2020.

[19] L. Flórez-Aristizábal, S. Cano, C. A. Collazos, A. F. Solano, and S. Brewster, "Designability: Framework for the design of accessible interactive tools to support teaching to children with disabilities," in Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, 2019, pp. 1–16.

[20] B. Zhang, G. Barbareschi, R. Ramirez Herrera, T. Carlson, and C. Holloway, "Understanding interactions for smart wheelchair navigation in crowds," in Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems, 2022, pp. 1–16.

[21] A. Sharif, S. S. Chintalapati, J. O. Wobbrock, and K. Reinecke, "Understanding screen-reader users' experiences with online data visualizations," in Proceedings of the 23rd International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '21. New York, NY, USA: Association for Computing Machinery, 2021. [Online]. Available: https://doi.org/10.1145/3441852.3471202

[22] C. Jung, S. Mehta, A. Kulkarni, Y. Zhao, and Y.-S. Kim, "Communicating visualizations without visuals: Investigation of visualization alternative text for people with visual impairments," IEEE Transactions on Visualization and Computer Graphics, vol. 28, no. 1, pp. 1095–1105, 2022.

[23] S. C. S. Joyner, A. Riegelhuth, K. Garrity, Y.-S. Kim, and N. W. Kim, "Visualization accessibility in the wild: Challenges faced by visualization designers," in Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems, 2022, pp. 1–19.

[24] E. Kim and K. F. McCoy, "Multimodal deep learning using images and text for information graphic classification," in Proceedings of the 20th International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '18. New York, NY, USA: Association for Computing Machinery, 2018, p. 143–148. [Online]. Available: https://doi.org/10.1145/3234695.3236357

[25] A. Sharif and B. Forouraghi, "evographs — a jquery plugin to create web accessible graphs," in 2018 15th IEEE Annual Consumer Communications & Networking Conference (CCNC), 2018, pp. 1–4.

[26] S. Mirri, S. Peroni, P. Salomoni, F. Vitali, and V. Rubano, "Towards accessible graphs in html-based scientific articles," in 2017 14th IEEE Annual Consumer Communications & Networking Conference (CCNC), 2017, pp. 1067–1072.

[27] T. Hermann, A. Hunt, and J. G. Neuhoff, The sonification handbook. Logos Verlag Berlin, 2011, vol. 1.

[28] C. Brown and A. Hurst, "Viztouch: Automatically generated tactile visualizations of coordinate spaces," in Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction, ser. TEI '12. New York, NY, USA: Association for Computing Machinery, 2012, p. 131–138. [Online]. Available: https://doi.org/10.1145/2148131.2148160

[29] L. Shi, I. Zelzer, C. Feng, and S. Azenkot, "Tickers and talker: An accessible labeling toolkit for 3d printed models," in Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, ser. CHI '16. New York, NY, USA: Association for Computing Machinery, 2016, p. 4896–4907. [Online]. Available: https://doi.org/10.1145/2858036.2858507

[30] A. Lundgard, C. Lee, and A. Satyanarayan, "Sociotechnical considerations for accessible visualization design," in 2019 IEEE Visualization Conference (VIS), 2019, pp. 16–20.

[31] S. Paneels and J. C. Roberts, "Review of designs for haptic data visualization," IEEE Transactions on Haptics, vol. 3, no. 2, pp. 119–137, 2010.

[32] M. E. Hahn, C. M. Mueller, and J. L. Gorlewicz, "The comprehension of stem graphics via a multisensory tablet electronic device by students with visual impairments," Journal of Visual Impairment & Blindness, vol. 113, no. 5, pp. 404–418, 2019.

[33] Y. Xie, H. Wang, C. Luo, Z. YANG, and Y. ZHAN, "Gazemetro: A gaze-based interactive system for metro map," in Proceedings of the 23rd International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '21. New York, NY, USA: Association for Computing Machinery, 2021. [Online]. Available: https://doi.org/10.1145/3441852.3476569

[34] K. Wu, M. H. Tran, E. Petersen, V. Koushik, and D. A. Szafir, "Data, data, everywhere: Uncovering everyday data experiences for people with intellectual and developmental disabilities," 2023.

[35] K. Wu, E. Petersen, T. Ahmad, D. Burlinson, S. Tanis, and D. A. Szafir, "Understanding data accessibility for people with intellectual and developmental disabilities," in Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, ser. CHI '21. New York, NY, USA: Association for Computing Machinery, 2021. [Online]. Available: https://doi.org/10.1145/3411764.3445743

[36] M. J. Page, J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, J. M. Tetzlaff, E. A. Akl, S. E. Brennan et al., "The prisma 2020 statement: an updated guideline for reporting systematic reviews," International journal of surgery, vol. 88, p. 105906, 2021.

[37] V. Braun and V. Clarke, "One size fits all? what counts as quality practice in (reflexive) thematic analysis?" Qualitative research in psychology, vol. 18, no. 3, pp. 328–352, 2021.

[38] A. Mancini, E. Frontoni, and P. Zingaretti, "Embedded multisensor system for safe point-to-point navigation of impaired users," IEEE Transactions on Intelligent Transportation Systems, vol. 16, no. 6, pp. 3543–3555, 2015.

[39] B. Shneiderman, "Data visualization's breakthrough moment in the covid-19 crisis." [Online]. Available: https://medium.com/nightingale/data-visualizations-breakthrough-moment

[40] ——, "The eyes have it: a task by data type taxonomy for information visualizations," in Proceedings 1996 IEEE Symposium on Visual Languages, 1996, pp. 336–343.

[41] J. O. Wobbrock and J. A. Kientz, "Research contributions in human-computer interaction," Interactions, vol. 23, no. 3, p. 38–44, apr 2016. [Online]. Available: https://doi.org/10.1145/2907069

[42] J. Lazar, S. Chakraborty, D. Carroll, R. Weir, B. Sizemore, and H. Henderson, "Development and evaluation of two prototypes for providing weather map data to blind users through sonification." Journal of Usability Studies, vol. 8, no. 4, 2013.

[43] R. Menzies, G. W. Tigwell, and M. Crabb, "Author reflections on creating accessible academic papers," ACM Trans. Access. Comput., vol. 15, no. 4, oct 2022. [Online]. Available: https://doi.org/10.1145/3546195

[44] I. Serna-Marjanović, A. Tanovic, and A. Cerimagic, "Accessibility standards and their implementation in custom data-driven maps," in 2020 43rd International Convention on Information, Communication and Electronic Technology (MIPRO), 2020, pp. 1674–1679.

[45] C. Chen, R. Wu, H. Khan, K. Truong, and F. Chevalier, "Vidde: Visualizations for helping people with copd interpret dyspnea during exercise," in Proceedings of the 23rd International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '21. New York, NY, USA: Association for Computing Machinery, 2021. [Online]. Available: https://doi.org/10.1145/3441852.3471204

[46] L. South and M. A. Borkin, "Photosensitive accessibility for interactive data visualizations," IEEE Transactions on Visualization and Computer Graphics, vol. 29, no. 1, pp. 374–384, 2023.

[47] A. Li, M. Saha, A. Gupta, and J. E. Froehlich, "Interactively modeling and visualizing neighborhood accessibility at scale: An initial study of washington dc," in Proceedings of the 20th International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '18. New York, NY, USA: Association for Computing Machinery, 2018, p. 444–446. [Online]. Available: https://doi.org/10.1145/3234695.3241000

[48] A. Sharif, A. Ramesh, T.-A. Nguyen, L. Chen, K. R. Zeng, L. Hou, and X. Xu, "Unlockedmaps: Visualizing real-time accessibility of urban rail transit using a web-based map," in Proceedings of the 24th International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '22. New York, NY, USA: Association for Computing Machinery, 2022. [Online]. Available: https://doi.org/10.1145/3517428.3550397

[49] R. Beaton, R. Merkel, J. Prathipati, A. Weckstein, and S. McCrickard, "Tracking mental engagement: A tool for young people with add and adhd," in Proceedings of the 16th International ACM SIGACCESS Conference on Computers amp; Accessibility, ser. ASSETS '14. New York, NY, USA: Association for Computing Machinery, 2014, p. 279–280. [Online]. Available: https://doi.org/10.1145/2661334.2661399

[50] J. Jones, S. Hall, M. Gentis, C. Reynolds, C. Gadwal, A. Hurst, J. Ronch, and C. Neylan, "Visualizations for self-reflection on mouse pointer performance for older adults," in Proceedings of the 14th International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '12. New York, NY, USA: Association for Computing Machinery, 2012, p. 287–288. [Online]. Available: https://doi.org/10.1145/2384916.2384996

[51] T. Schlippe, S. Alessai, G. El-Taweel, M. Wölfel, and W. Zaghouani, "Visualizing voice characteristics with type design in closed captions for arabic," in 2020 International Conference on Cyberworlds (CW), 2020, pp. 196–203.

[52] J. Lazar, J. H. Feng, and H. Hochheiser, Research methods in human-computer interaction. Morgan Kaufmann, 2017.

[53] B. H. Ugalde, A. A. Vinluan, and J. T. Carpio, "Graph representation of road network for mobility-impaired persons," in 2021 4th International Conference on Information and Computer Technologies (ICICT), 2021, pp. 194–198.

[54] R. Guo, Y. Yang, J. Kuang, X. Bin, D. Jain, S. Goodman, L. Findlater, and J. Froehlich, "Holosound: Combining speech and sound identification for deaf or hard of hearing users on a head-mounted display," in Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '20. New York, NY, USA: Association for Computing Machinery, 2020. [Online]. Available: https://doi.org/10.1145/3373625.3418031

[55] A. Sears and V. Hanson, "Representing users in accessibility research," in Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ser. CHI '11. New York, NY, USA: Association for Computing Machinery, 2011, p. 2235–2238. [Online]. Available: https://doi.org/10.1145/1978942.1979268

[56] F. Elavsky, C. Bennett, and D. Moritz, "How accessible is my visualization? evaluating visualization accessibility with chartability," in Computer Graphics Forum, vol. 41, no. 3. Wiley Online Library, 2022, pp. 57–70.

[57] N. Tovanich, N. Heulot, J.-D. Fekete, and P. Isenberg, "Visualization of blockchain data: a systematic review," IEEE transactions on visualization and computer graphics, vol. 27, no. 7, pp. 3135–3152, 2019.

[58] B. Haber Ugalde, A. Alcause Vinluan, and J. Torres Carpio, "Wheelchair navigation system using node combination technique for people with motor disabilities," in Proceedings of the 13th International Conference on Computer Modeling and Simulation, ser. ICCMS '21. New York, NY, USA: Association for Computing Machinery, 2021, p. 203–209. [Online]. Available: https://doi.org/10.1145/3474963.3474991

[59] A. Miyata, K. Okugawa, Y. Yamato, T. Maeda, Y. Murayama, M. Aibara, M. Furuichi, and Y. Murayama, "A crowdsourcing platform for constructing accessibility maps supporting multiple participation modes," in Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems, ser. CHI EA '21. New York, NY, USA: Association for Computing Machinery, 2021. [Online]. Available: https://doi.org/10.1145/3411763.3451688

[60] A. Repenning and A. Ioannidou, "Mobility agents: Guiding and tracking public transportation users," in Proceedings of the Working Conference on Advanced Visual Interfaces, ser. AVI '06. New York, NY, USA: Association for Computing Machinery, 2006, p. 127–134. [Online]. Available: https://doi.org/10.1145/1133265.1133292

[61] N. Rodriguez, "Identifying accessibility conditions for children with multiple disabilities: A virtual reality wheelchair simulator," in 2018 IEEE International Symposium on Mixed

and Augmented Reality Adjunct (ISMAR-Adjunct), 2018, pp. 370–372.

[62] Y. Han, C. B. Han, C. Chen, P. W. Lee, M. Hogarth, A. A. Moore, N. Weibel, and E. Farcas, "Towards visualization of time–series ecological momentary assessment (ema) data on standalone voice–first virtual assistants," in Proceedings of the 24th International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '22. New York, NY, USA: Association for Computing Machinery, 2022. [Online]. Available: https://doi.org/10.1145/3517428.3550398

[63] I. Afyouni, F. U. Rehman, A. Qamar, A. Ahmad, M. A. Rahman, and S. Basalamah, "A gis-based serious game recommender for online physical therapy," in Proceedings of the Third ACM SIGSPATIAL International Workshop on the Use of GIS in Public Health, ser. HealthGIS '14. New York, NY, USA: Association for Computing Machinery, 2014, p. 1–10. [Online]. Available: https://doi.org/10.1145/2676629.2676634

[64] N. M. Gil, N. A. Hine, J. L. Arnott, J. Hanson, R. G. Curry, T. Amaral, and D. Osipovic, "Data visualisation and data mining technology for supporting care for older people," in Proceedings of the 9th International ACM SIGACCESS Conference on Computers and Accessibility, ser. Assets '07. New York, NY, USA: Association for Computing Machinery, 2007, p. 139–146. [Online]. Available: https://doi.org/10.1145/1296843.1296868

[65] L. Pareto, "Graphical arithmetic for learners with dyscalculia," in Proceedings of the 7th International ACM SIGACCESS Conference on Computers and Accessibility, ser. Assets '05. New York, NY, USA: Association for Computing Machinery, 2005, p. 214–215. [Online]. Available: https://doi.org/10.1145/1090785.1090836

[66] K. Y. Fung, Z. A. Wen, H. Li, X. Wang, S. Song, and H. Qu, "Designing a data visualization dashboard for pre-screening hong kong students with specific learning disabilities," in Proceedings of the 24th International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '22. New York, NY, USA: Association for Computing Machinery, 2022. [Online]. Available: https://doi.org/10.1145/3517428.3550361

[67] A. Siu, G. S-H Kim, S. O'Modhrain, and S. Follmer, "Supporting accessible data visualization through audio data narratives," in Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems, ser. CHI '22. New York, NY, USA: Association for Computing Machinery, 2022. [Online]. Available: https://doi.org/10.1145/3491102.3517678

[68] B. Shneiderman and J. Hullman, "The purpose of visualization is insight, not pictures: An interview with ben shneiderman," Aug 2019. [Online]. Available: https://interactions.acm.org/blog/view/

[69] S. McDonald, J. Dutterer, A. Abdolrahmani, S. K. Kane, and A. Hurst, "Tactile aids for visually impaired graphical design education," in Proceedings of the 16th International ACM SIGACCESS Conference on Computers & Accessibility, ser. ASSETS '14. New York, NY, USA: Association for Computing Machinery, 2014, p. 275–276. [Online]. Available: https://doi.org/10.1145/2661334.2661392

[70] A. Sharif, O. H. Wang, A. T. Muongchan, K. Reinecke, and J. O. Wobbrock, "Voxlens: Making online data visualizations accessible with an interactive javascript plug-in," in Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems, 2022, pp. 1–19.

[71] M. Saha, S. Patil, E. Cho, E. Y.-Y. Cheng, C. Horng, D. Chauhan, R. Kangas, R. McGovern, A. Li, J. Heer, and J. E. Froehlich, "Visualizing urban accessibility: Investigating multi-stakeholder perspectives through a map-based design probe study," in Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems, ser. CHI '22. New York, NY, USA: Association for Computing Machinery, 2022. [Online]. Available: https://doi.org/10.1145/3491102.3517460

[72] Z. Li, S. Connell, W. Dannels, and R. Peiris, "Soundvizvr: Sound indicators for accessible sounds in virtual reality for deaf or hard-of-hearing users," in Proceedings of the 24th International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '22. New York, NY, USA: Association for Computing Machinery, 2022. [Online]. Available: https://doi.org/10.1145/3517428.3544817

[73] P. K. Sridhar, B. Petry, P. V. S. Pakianathan, A. S. Kartolo, and S. Nanayakkara, "Towards one-pixel-displays for sound information visualization," in Proceedings of the 28th Australian Conference on Computer-Human Interaction, ser. OzCHI '16. New York, NY, USA: Association for Computing Machinery, 2016, p. 91–95. [Online]. Available: https://doi.org/10.1145/3010915.3010980

[74] M. Wagner, D. Slijepcevic, B. Horsak, A. Rind, M. Zeppelzauer, and W. Aigner, "Kavagait: Knowledge-assisted visual analytics for clinical gait analysis," IEEE Transactions on Visualization and Computer Graphics, vol. 25, no. 3, pp. 1528–1542, 2019.

[75] R. Neßelrath, J. Haupert, J. Frey, and B. Brandherm, "Supporting persons with special needs in their daily life in a smart home," in 2011 Seventh International Conference on Intelligent Environments, 2011, pp. 370–373.

[76] G. Yang, M. Iwabuchi, R. Hirabayashi, K. Nakamura, K. Taniguchi, S. Sano, and T. Aoki, "Motion history to improve communication and switch access for people with severe and multiple disabilities," in Proceedings of the 16th International ACM SIGACCESS Conference on Computers amp; Accessibility, ser. ASSETS '14. New York, NY, USA: Association for Computing Machinery, 2014, p. 309–310. [Online]. Available: https://doi.org/10.1145/2661334.2661351

[77] K. Mack, E. J. McDonnell, L. Findlater, and H. D. Evans, "Chronically under-addressed: Considerations for hci accessibility practice with chronically ill people," in Proceedings of the 24th International ACM SIGACCESS Conference on Computers and Accessibility, 2022, pp. 1–15.

[78] M. Mott, J. Tang, S. Kane, E. Cutrell, and M. Ringel Morris, ""i just went into it assuming that i wouldn't be able to have the full experience" understanding the accessibility of virtual reality for people with limited mobility," in Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility, 2020, pp. 1–13.

[79] H. Lim, L. Kakonge, Y. Hu, L. Turkstra, M. Duff, C. Toma, and B. Mutlu, "So, i can feel normal: Participatory design for accessible social media sites for individuals with traumatic brain injury," in Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems, ser. CHI '23. New York, NY, USA: Association for Computing Machinery, 2023. [Online]. Available: https://doi.org/10.1145/3544548.3581222

[80] R.-D. Vatavu, O.-C. Ungurean, and L.-B. Bilius, "Interactive public displays and wheelchair users: Between direct, personal and indirect, assisted interaction," in Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology, ser. UIST '22. New York, NY, USA: Association for Computing Machinery, 2022. [Online]. Available: https://doi.org/10.1145/3526113.3545662

[81] Y. Lei, S. He, M. Khamis, and J. Ye, "An end-to-end review of gaze estimation and its interactive applications on handheld mobile devices," ACM Comput. Surv., jun 2023, just Accepted. [Online]. Available: https://doi.org/10.1145/3606947

[82] E. Corbett and A. Weber, "What can i say? addressing user experience challenges of a mobile voice user interface for accessibility," in Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services, ser. MobileHCI '16. New York, NY, USA: Association for Computing Machinery, 2016, p. 72–82. [Online]. Available: https://doi.org/10.1145/2935334.2935386

[83] A. Sears, C.-M. Karat, K. Oseitutu, A. Karimullah, and J. Feng, "Productivity, satisfaction, and interaction strategies of individuals with spinal cord injuries and traditional users interacting with speech recognition software," Universal Access in the information Society, vol. 1, pp. 4–15, 2001.

[84] J. Zong, C. Lee, A. Lundgard, J. Jang, D. Hajas, and A. Satyanarayan, "Rich screen reader experiences for accessible data visualization," in Computer Graphics Forum, vol. 41, no. 3. Wiley Online Library, 2022, pp. 15–27.

[85] T. Munzner, Visualization analysis and design. CRC press, 2014.

[86] W. S. Cleveland and R. McGill, "Graphical perception: Theory, experimentation, and application to the development of graphical methods," Journal of the American statistical association, vol. 79, no. 387, pp. 531–554, 1984.

[87] Z. Zhang, "Tapsonic: One dimensional finger mounted multimodal line chart reader," in Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '20. New York, NY, USA: Association for Computing Machinery, 2020. [Online]. Available: https://doi.org/10.1145/3373625.3417075

[88] I. Abu Doush, E. Pontelli, D. Simon, T. C. Son, and O. Ma, "Making microsoft excel™: Multimodal presentation of charts," in Proceedings of the 11th International ACM SIGACCESS Conference on Computers and Accessibility, ser. Assets '09. New York, NY, USA: Association for Computing Machinery, 2009, p. 147–154. [Online]. Available: https://doi.org/10.1145/1639642.1639669

[89] S. A. Wall and S. A. Brewster, "Tac-tiles: Multimodal pie charts for visually impaired users," in Proceedings of the 4th Nordic Conference on Human-Computer Interaction: Changing Roles, ser. NordiCHI '06. New York, NY, USA: Association for Computing Machinery, 2006, p. 9–18. [Online]. Available: https://doi.org/10.1145/1182475.1182477

[90] J. L. Tennison and J. L. Gorlewicz, "Non-visual perception of lines on a multimodal touchscreen tablet," ACM Trans. Appl. Percept., vol. 16, no. 1, feb 2019. [Online]. Available: https://doi.org/10.1145/3301415

[91] L. M. Holloway, C. Goncu, A. Ilsar, M. Butler, and K. Marriott, "Infosonics: Accessible infographics for people who are blind using sonification and voice," in Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems, ser. CHI '22. New York, NY, USA: Association for Computing Machinery, 2022. [Online]. Available: https://doi.org/10.1145/3491102.3517465

[92] E. D. Z. Chase, A. F. Siu, A. Boadi-Agyemang, G. S.-H. Kim, E. J. Gonzalez, and S. Follmer, "Pantoguide: A haptic and audio guidance system to support tactile graphics exploration," in Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '20. New York, NY, USA: Association for Computing Machinery, 2020. [Online]. Available: https://doi.org/10.1145/3373625.3418023

[93] T. Götzelmann, "Visually augmented audio-tactile graphics for visually impaired people," ACM Trans. Access. Comput., vol. 11, no. 2, jun 2018. [Online]. Available: https://doi.org/10.1145/3186894

[94] C. Engel, E. F. Müller, and G. Weber, "Svgplott: An accessible tool to generate highly adaptable, accessible audio-tactile charts for and from blind and visually impaired people," in Proceedings of the 12th ACM International Conference on PErvasive Technologies Related to Assistive Environments, ser. PETRA '19. New York, NY, USA: Association for Computing Machinery, 2019, p. 186–195. [Online]. Available: https://doi.org/10.1145/3316782.3316793

[95] C. F. Greenbacker, P. Wu, S. Carberry, K. F. McCoy, S. Elzer, D. D. McDonald, D. Chester, and S. Demir, "Improving the accessibility of line graphs in multimodal documents," in Proceedings of the Second Workshop on Speech and Language Processing for Assistive Technologies, 2011, pp. 52–62.

[96] C. F. Greenbacker, "Summarizing multimodal documents in popular media for people with visual impairments," SIGACCESS Access. Comput., no. 102, p. 13–16, jan 2012. [Online]. Available: https://doi.org/10.1145/2140446.2140449

[97] Z. B. Fredj and D. A. Duce, "Grassml: accessible smart schematic diagrams for all," in Proceedings of the 2006 international cross-disciplinary workshop on Web accessibility (W4A): Building the mobile web: rediscovering accessibility?, 2006, pp. 57–60.

[98] A. Sharif, O. H. Wang, and A. T. Muongchan, ""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, ser. ASSETS '22. New York, NY, USA: Association for Computing Machinery, 2022. [Online]. Available: https://doi.org/10.1145/3517428.3550360

[99] K. Ohshiro, A. Hurst, and L. DuBois, "Making math graphs more accessible in remote learning: Using sonification to introduce discontinuity in calculus," in Proceedings of the 23rd International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '21. New York, NY, USA: Association for Computing Machinery, 2021. [Online]. Available: https://doi.org/10.1145/3441852.3476533

[100] B. N. Walker and L. M. Mauney, "Universal design of auditory graphs: A comparison of sonification mappings for visually impaired and sighted listeners," ACM Trans. Access. Comput., vol. 2, no. 3, mar 2010. [Online]. Available: https://doi.org/10.1145/1714458.1714459

[101] J. C. Adams, B. D. Allen, B. C. Fowler, M. C. Wissink, and J. J. Wright, "The sounds of sorting algorithms: Sonification as a pedagogical tool," in Proceedings of the 53rd ACM Technical Symposium on Computer Science Education - Volume 1, ser. SIGCSE 2022. New York, NY, USA: Association for Computing Machinery, 2022, p. 189–195. [Online]. Available: https://doi.org/10.1145/3478431.3499304

[102] I. Abu Doush, E. Pontelli, T. C. Son, D. Simon, and O. Ma, "Multimodal presentation of two-dimensional charts: An investigation using open office xml and microsoft excel," ACM Trans. Access. Comput., vol. 3, no. 2, nov 2010. [Online]. Available: https://doi.org/10.1145/1857920.1857925

[103] K. Araki, T. Watanabe, and K. Minatani, "Development of tactile graph generation software using the r statistics software environment," in Proceedings of the 16th International ACM SIGACCESS Conference on Computers & Accessibility, ser. ASSETS '14. New York, NY, USA: Association for Computing Machinery, 2014, p. 251–252. [Online]. Available: https://doi.org/10.1145/2661334.2661389

[104] G. Petit, A. Dufresne, V. Levesque, V. Hayward, and N. Trudeau, "Refreshable tactile graphics applied to schoolbook illustrations for students with visual impairment," in Proceedings of the 10th International ACM SIGACCESS Conference on Computers and Accessibility, ser. Assets '08. New York, NY, USA: Association for Computing Machinery, 2008, p. 89–96. [Online]. Available: https://doi.org/10.1145/1414471.1414489

[105] D. Guinness, A. Muehlbradt, D. Szafir, and S. K. Kane, "Robographics: Using mobile robots to create dynamic tactile graphics," in Proceedings of the 21st International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '19. New York, NY, USA: Association for Computing Machinery, 2019, p. 673–675. [Online]. Available: https://doi.org/10.1145/3308561.3354597

[106] C. Goncu and K. Marriott, "Tactile chart generation tool," in Proceedings of the 10th International ACM SIGACCESS Conference on Computers and Accessibility, ser. Assets '08. New York, NY, USA: Association for Computing Machinery, 2008, p. 255–256. [Online]. Available: https://doi.org/10.1145/1414471.1414525

[107] K. Araki and T. Watanabe, "Comparison of reading accuracy between tactile pie charts and tactile band charts," in Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '13. New York, NY, USA: Association for Computing Machinery, 2013. [Online]. Available: https://doi.org/10.1145/2513383.2513404

[108] D. K. McGookin and S. A. Brewster, "Soundbar: Exploiting multiple views in multimodal graph browsing," in Proceedings of the 4th Nordic Conference on Human-Computer Interaction: Changing Roles, ser. NordiCHI '06. New York, NY, USA: Association for Computing Machinery, 2006, p. 145–154. [Online]. Available: https://doi.org/10.1145/1182475.1182491

[109] F. Wang, H. Nagano, K. Kashino, and T. Igarashi, "Visualizing video sounds with sound word animation to enrich

user experience," IEEE Transactions on Multimedia, vol. 19, no. 2, pp. 418–429, 2016.

[110] S. Carberry, S. Elzer Schwartz, K. Mccoy, S. Demir, P. Wu, C. Greenbacker, D. Chester, E. Schwartz, D. Oliver, and P. Moraes, "Access to multimodal articles for individuals with sight impairments," ACM Trans. Interact. Intell. Syst., vol. 2, no. 4, jan 2013. [Online]. Available: https://doi.org/10.1145/2395123.2395126

[111] L. Ferres, P. Verkhogliad, G. Lindgaard, L. Boucher, A. Chretien, and M. Lachance, "Improving accessibility to statistical graphs: The igraph-lite system," in Proceedings of the 9th International ACM SIGACCESS Conference on Computers and Accessibility, ser. Assets '07. New York, NY, USA: Association for Computing Machinery, 2007, p. 67–74. [Online]. Available: https://doi.org/10.1145/1296843.1296857

[112] A. Sharif and B. Forouraghi, "evographs—a jquery plugin to create web accessible graphs," in 2018 15th IEEE Annual Consumer Communications & Networking Conference (CCNC). IEEE, 2018, pp. 1–4.

[113] D. Fan, A. Fay Siu, S. O'Modhrain, and S. Follmer, "Constructive visualization to inform the design and exploration of tactile data representations," in Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '20. New York, NY, USA: Association for Computing Machinery, 2020. [Online]. Available: https://doi.org/10.1145/3373625.3418027

[114] Z. Wang, B. Li, T. Hedgpeth, and T. Haven, "Instant tactile-audio map: Enabling access to digital maps for people with visual impairment," in Proceedings of the 11th International ACM SIGACCESS Conference on Computers and Accessibility, ser. Assets '09. New York, NY, USA: Association for Computing Machinery, 2009, p. 43–50. [Online]. Available: https://doi.org/10.1145/1639642.1639652

[115] N. Kaklanis, K. Votis, P. Moschonas, and D. Tzovaras, "Hapticriamaps: Towards interactive exploration of web world maps for the visually impaired," in Proceedings of the International Cross-Disciplinary Conference on Web Accessibility, ser. W4A '11. New York, NY, USA: Association for Computing Machinery, 2011. [Online]. Available: https://doi.org/10.1145/1969289.1969316

[116] W. Grussenmeyer, J. Garcia, and F. Jiang, "Feasibility of using haptic directions through maps with a tablet and smart watch for people who are blind and visually impaired," in Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services, ser. MobileHCI '16. New York, NY, USA: Association for Computing Machinery, 2016, p. 83–89. [Online]. Available: https://doi.org/10.1145/2935334.2935367

[117] T. Calle-Jimenez and S. Luján-Mora, "Accessible online indoor maps for blind and visually impaired users," in Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '16. New York, NY, USA: Association for Computing Machinery, 2016, p. 309–310. [Online]. Available: https://doi.org/10.1145/2982142.2982201

[118] F. Ahmed, M. S. Mahmud, R. Al-Fahad, S. Alam, and M. Yeasin, "Image captioning for ambient awareness on a sidewalk," in 2018 1st International Conference on Data Intelligence and Security (ICDIS). IEEE, 2018, pp. 85–91.

[119] M. Konecki, C. LaPierre, and K. Jervis, "Accessible data visualization in higher education," in 2018 41st international convention on information and communication technology, electronics and microelectronics (MIPRO). IEEE, 2018, pp. 0733–0737.

[120] C. Bernareggi, D. Ahmetovic, and S. Mascetti, "graph: Haptic exploration and editing of 3d chemical diagrams," in Proceedings of the 21st International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '19. New York, NY, USA: Association for Computing Machinery, 2019, p. 312–317. [Online]. Available: https://doi.org/10.1145/3308561.3353811

[121] Y. Moskovitch and B. N. Walker, "Evaluating text descriptions of mathematical graphs," in Proceedings of the 12th International ACM SIGACCESS Conference on Computers and Accessibility, ser. ASSETS '10. New York, NY, USA: Association for Computing Machinery, 2010, p. 259–260. [Online]. Available: https://doi.org/10.1145/1878803.1878860

[122] B. J. Tomlinson, J. Batterman, Y. C. Chew, A. Henry, and B. N. Walker, "Exploring auditory graphing software in the classroom: The effect of auditory graphs on the classroom environment," ACM Trans. Access. Comput., vol. 9, no. 1, nov 2016. [Online]. Available: https://doi.org/10.1145/2994606

[123] W. J. Kim, I. K. Kim, M. J. Kim, and E. Lee, "Effect of ux design guideline on the information accessibility for the visually impaired in the mobile health apps," in 2018 IEEE international conference on bioinformatics and biomedicine (BIBM). IEEE, 2018, pp. 1103–1106.

[124] V. Upadhyay and M. Balakrishnan, "Accessibility of healthcare facility for persons with visual disability," in 2021 IEEE International Conference on Pervasive Computing and Communications Workshops and other Affiliated Events (PerCom Workshops). IEEE, 2021, pp. 87–92.

Brianna Lynn Wimer is a Google Ph.D. Fellow at the University of Notre Dame, working towards her Ph.D. in Computer Science and Engineering. She received her Bachelor's degree in Computer Science from the University of Alabama in 2021. Her research focuses on the intersection of accessibility and data visualization.

Laura South is a Ph.D. candidate at Northeastern University in the Data Visualization Lab within Khoury College of Computer Sciences. Her research interests include accessibility, data visualization, and online safety.

Keke Wu is a final-year Ph.D. candidate at the University of North Carolina at Chapel Hill. Her research aims to make data accessible to individuals with diverse cognitive abilities, especially those with Intellectual and Developmental Disabilities (IDD), through storytelling, aesthetics, and creative technology.

Danielle Albers Szafir is with the University of North Carolina at Chapel Hill. Her research explores the interplay of visualization and cognitive science, including perceptual modeling, cognitive accessibility, and physical data interfaces. Szafir received her Ph.D. in Computer Sciences at the University of Wisconsin-Madison. She is a member of the IEEE. Contact her at danielle.szafir@cs.unc.edu.

Michelle A. Borkin is an associate professor at the Khoury College of Computer Sciences at Northeastern University. She works on the development of novel visualization techniques and tools to enable new insights and discoveries in data. Borkin received her Ph.D in Computer Science at Harvard University.

Ronald Metoyer is a Professor of Computer Science and is the Vice President and Associate Provost for Teaching and Learning at the University of Notre Dame. He received his Ph.D. in Computer Science at Georgia Institute of Technology. His research falls under the general area of Human Computer Interaction with an emphasis on Information Visualization. He is a member of the IEEE.