Digital Technologies for Deaf and Hard of Hearing Children: a Systematic Review, Critical Reflections, and Future Research Directions

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Abstract

Digital technologies in Human-Computer Interaction (HCI) have the potential to support the development and well-being of Deaf and Hard of Hearing (DHH) children. Yet, there has yet to be a systematic review of the field. A shared understanding of current research is needed to develop a future vision. In this review, we analyzed 42 papers from the ACM Digital Library and the top 20 HCI Conferences and Journals, spanning the past 24 years, to investigate the trends, methods, and the level of inclusion of DHH children. Our review reveals that sign language learning platforms dominate the current technological effort. Moreover, children are not yet fully involved in the design process of these technologies and are mostly considered users and testers.We also capture a gap in integrating Deaf culture and child development in prior research. We conclude by critically examining literature gaps and offering guidance for future research.

CCS Concepts

• **Human-centered computing** → **Accessibility theory, concepts and paradigms**; • **Social and professional topics** → **People with disabilities**; **Children**.

Keywords

Deaf and hard of hearing, Children, Systematic review, Accessibility

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1 Introduction

Over 5% of the world's population - 430 million people - are deaf and hard of hearing (DHH), including 34 million children with hearing loss [90]. Research in Human-Computer Interaction (HCI) has proposed many digital technologies to tackle the real-world accessibility challenges of DHH people [23, 75] while addressing broader social issues of equality, diversity, and inclusion. Several of these innovative new solutions aim to improve communication (e.g., [89, 93]) and learning (e.g., [48, 56]), which can be particularly relevant for children. Indeed, over the past 30 years, the rise of research fields such as Child-Computer Interaction (CCI) and Accessibility have contributed to a better understanding of how to design technologies for children and DHH individuals, respectively.

However, there is currently a lack of understanding of the state of the art of technologies for DHH children. On the one hand, existing reviews for DHH individuals tend to focus on adults and sign language processing (e.g., [6, 99]). These reviews are often limited in scope and restricted to technical reviews of algorithms for sign language recognition. Overall, literature reviews focusing on DHH users are rare [23], particularly for subgroups such as children. On the other hand, prior HCI reviews of research into children focus on other disabilities (e.g., autistic children [107]) or, more generally, on children with *"special (education) needs"* [18, 21]. While these reviews map out methods, approaches, and technologies when designing for children with disabilities, they do not explore the unique socio-cultural challenges of growing up in a mainly hearing society. Sign languages are minority languages used primarily by Deaf people who often identify as members of a

Deaf cultural minority [1]. This is particularly relevant for children as many communication barriers can result from using non-majority languages in mainstream schools, putting Deaf children at risk of social isolation. Moreover, deaf education systems often fail to support the acquisition of a first language properly, let alone enable proper bilingual education, resulting in low literacy rates for Deaf children [46]. When considering family settings, these may also not favour accessing Deaf communities or learning sign language, as most children are born to hearing parents [80]. Thus, developing digital technologies for DHH children's development is socio-culturally challenging.

To our knowledge, no systematic review of digital technologies designed for DHH children exists. Thus, it is hard to know what challenges are being tackled, the current use of technologies, design practices, research methods, and how children are being involved. Such a lack of knowledge complicates setting a shared vision and agenda for research into HCI and DHH children. In this paper, we present the results from a systematic review of digital technologies for DHH children to identify trends, norms, and research gaps, providing an entry point for understanding the field and informing future research directions. Our key research questions include: (1) what are the research objectives, contributions, and technology types in developing technologies for DHH children within HCI? (2) what design and research methods are used throughout the development process? and (3) what are the role and characteristics of DHH children involved in designing new digital technologies?

To answer these questions we reviewed research published in the ACM Digital Library, which contains interdisciplinary HCI, CCI, and Accessibility research, as well as HCI top 20 Conferences and Journals. We followed the PRISMA methodology [82] to create a dataset of 42 papers from 2000 to March 2024. Four researchers manually coded the dataset to capture the research foci (e.g., type of contribution, technologies, challenges being addressed), methodological features (e.g., identifying needs, design, and evaluation methods), and the roles of research participants (e.g., users, testers, informants, design partners [57, 71]).

We found that most digital technologies are designed to provide sign language learning tools for DHH children. While sign language development is important for their cognitive development, it alone does not promote communication and interaction between DHH children and their broader social contexts. Future efforts should also focus on creating incidental language learning environments to support more natural, social language acquisition [7]. Our results also show that in HCI research for DHH children, they are often absent or play a passive role in the needs assessment process, with limited direct engagement in designing technologies for them. DHH children are primarily involved as users and testers, while hearing adults frequently act as proxies for children's needs and interests. This contradicts the current calls in HCI to give children with impairments a more active voice in the design process [71, 107, 117]. Moreover, we found a lack of engagement and integration with the Deaf culture and child development research in developing digital technologies for DHH children. Results show that only one paper explicitly addresses Deaf culture. Similarly, only one paper discusses children's collaborative learning and social interactions, and the majority of research fails to account for the varying needs of children at different developmental stages, falling behind existing calls from critical disability scholars [30, 32, 43, 76] and child-computer interaction studies [87, 113, 119].

Overall, this paper contributes with a characterization of the current state of the art on digital technologies for DHH children. As the fields of Accessibility and CCI continue to expand, our analysis provides insights across individual research efforts, highlights current gaps and trends, and aims to inspire future work serving this user group. Thus, we explicitly draw implications for future research at the intersection of HCI, Accessibility, and CCI. Finally, with recent calls for HCI and Accessibility research to consider critical approaches to the design of assistive technologies [19, 52, 117], justice and agency throughout and beyond the design process [20, 106, 109], and the role of culture and linguistic identity of DHH people [23, 24, 91], we contribute with a reflection on how prior research views disability, Deaf culture, and the role of DHH children in the design of digital technologies. These contributions are relevant to researchers in HCI and related fields, such as CCI and Accessibility, as well as designers of assistive technologies that aim to create digital technologies with/for DHH children.

2 Background & Related work

Developing digital technologies for DHH children requires knowledge of their life experiences growing up as a linguistic minority group. This knowledge can aid technologists in creating systems that match the needs and desires of DHH children while taking into account their broader sociocultural context. In this section, we summarize this background and discuss existing reviews on Child-Computer interaction and its intersection with accessibility research.

2.1 Deaf Culture and the Sociocultural Context of DHH Children

Deaf individuals form cultural minority groups that are bound by common (sign) languages and life experiences [13]. Sign languages are a key component of Deaf cultures, influencing, for example, social behaviors, collective norms, arts, education, and other manifestations of human knowledge. However, growing up as a linguistic and cultural minority can be challenging. Restriction of sign language use and literacy has been a significant form of oppression against the Deaf community, particularly in children. Such oppression is often grounded on an unsupported belief that sign language acquisition interferes with spoken language acquisition [51, 59]. In fact, bilinguals are associated with better cognitive outcomes when compared with monolinguals [5], especially at earlier ages of active bilingualism [72].

Moreover, it is noteworthy that most DHH children (90%-96%) are born to hearing parents with no prior experience of deafness [80]. Such a deficit perspective on parents and children's emerging bilingualism has aligned with oralist/monolingual ideologies, leading to the promotion of cochlear implants and spoken language training as the sole option for deaf children [68, 77]. Such denial of multiculturalism and multilingualism against children is viewed as

[1]We use uppercase "Deaf" to refer to members of a cultural minority group, and lowercase "deaf" to refer to audiological (hearing) status.

a form of social violence by the Deaf community with severe developmental consequences. Language deprivation and delays affect the development of neuro-linguistic structures in the brain [105] and mental health issues across an individual's life span [74, 75].

Many people perceive deafness not as a disability but as a cultural identity [41], to be embraced and celebrated for its numerous advantages [17]. Indeed, we have witnessed a growing number of accessibility research calling for the inclusion of disabled people and disability studies within the development of assistive technologies. This resulted in a clear shift from the *medical model* of disability that overemphasizes "fixing" the individual rather than tackling broader societal and systemic issues related to access and oppression [76]. The first meaningful shift was towards the *social model* of disability, which sees disability as a social issue and construction, emphasizing removing barriers and improving attitudes to increase the quality of life for disabled people. More recently, critical scholar Alison Kafer proposed the *political/relational model* of disability, which locates disability as not occurring within an individual or infrastructure but instead produced through interactions [60]. In other words, being "disabled" can constantly change based on material and social context (e.g., people, relationships, behaviors, and norms). Building on such views, accessibility researchers highlighted the importance of interdependency as a complement to the traditional goal of building technologies to support independence [19]; and also identified further opportunities to involve disability studies in the design of digital technologies [52]. Our systematic review of HCI literature leverages these recent calls to action and explores issues of representation while reflecting on how previous work with DHH children views disability and Deaf culture.

2.2 Child-Computer Interaction and Accessibility Research

Child-Computer Interaction (CCI) is a steadily growing subarea of HCI, which focuses on children as an important emerging user group [71]. Several reviews in CCI seek to understand the methods, techniques, and roles of children in the design process in order to provide resources for future designers and researchers in CCI. For example, Tsvyatkova and Storni reviewed a wide range of CCI methods, techniques and tools developed/adapted for involving children in the design process, as well as the factors involved in conducting co-design activities (e.g., number of participants, ages, and setting) [112]. In addition, there has been work focusing on the role of children in design activities. Lehnert et al. [71] found that involving children in the design process by having them take on the role of informants or design partners promotes more active participation in the design process. Conversely, when children take more passive roles, such as users or testers, it is often because adult stakeholders perceive themselves as the experts. This is particularly common with specific groups of children, such as those with autism spectrum disorders (ASD), suggesting that the process of involving these children in design may need to be approached differently.

This was also emphasized in Benton et al.'s [21] review on methods and techniques for involving children with special educational needs or disabilities (SEND) in the design process. which revealed that adults represented a significant proportion of participants in the design process. The authors recommended the use of participatory design methods to give children the opportunity to demonstrate knowledge, skills and/or abilities that they may not have been previously recognized for, and to shift the balance of power in the relationship between children and adults. In addition to the over-representation of adults, Börjesson et. al [22] found that children with high-functioning autism aged 8–12 years are the most often involved in the design process, while other developmentally diverse children tended to play a more passive role – often being observed. Another key finding was that children with mixed abilities are rarely included in the design process. Baykal et al. [18] come to a similar conclusion that collaborative technologies for children with special needs are an area of growing interest, but that the target group is mainly autistic boys aged 6–12 years, proposing the need for more research with other special needs groups.

Overall, while there are prior systematic reviews on digital technologies for children with disabilities, to our knowledge, there is no comprehensive overview of HCI literature focusing on DHH children. Critical aspects, such as the role of DHH children in HCI design, the techniques and methods employed, and the specific challenges faced by this user group remain largely unexplored. To address this gap, we aim to systematically review the existing HCI literature and outline future research directions to guide researchers and designers in supporting the development of DHH children.

3 Methodology

To understand the current body of research in HCI for DHH children, we conducted a systematic literature review targeting research published in the ACM Digital Library (ACM DL) and Google Scholar's top 20 ranking in HCI Conferences and Journals [103]. The ACM and its SIGs host over 170 yearly events focused on various Computer Science disciplines and their subfields, which are particularly relevant to our review, such as HCI, Accessibility, and CCI. It offers a dedicated repository of 786,000 full-text articles and 3.2 million tracked publications. Unlike broader databases (e.g. SpringerLink or Scopus), ACM focuses specifically on digital technologies and is highly respected within their subcommunities, ensuring that articles retrieved from these databases are well circulated and peer-reviewed by experts. To complement the ACM DL database, we included top HCI venues from Google Scholar's top 20 rankings, ensuring greater diversity within the field while upholding high research standards. We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to guide our selection and screening methods [82] (see Figure 1 for an illustration of our review methodology [44]).

3.1 Identification Process

We conducted a systematic search for research published in the ACM Digital Library and Google Scholar top 20 ranking in HCI Conferences and Journals (including 9 that are already indexed in the ACM DL), including IEEE Transactions on Automatic Control (IEEE TOAC), International Journal of Human-Computer Studies (IJHCS), Behaviour & Information Technology (BIT), International Journal of Human–Computer Interaction (IJHCI), Virtual Reality (VR), International Journal of Interactive Mobile Technologies (iJIM), IEEE Virtual Reality (IEEE VR), Transactions on Human-Machine Systems (IEEE THMS), International Conference on Human-Computer

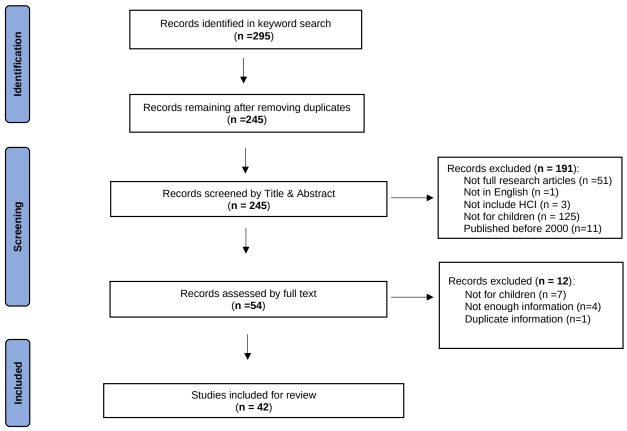

Figure 1: The PRISMA flow diagram used in this literature review

Interaction (HCII), International Journal of Child-Computer Interaction (IJCCI), Multimodal Technologies and Interaction (MTI) conferences and journals). We completed our search for papers on March 19, 2024. We searched for the relevant keywords "deafness", "hard of hearing", "DHH", and "children" and their variants in the title, abstract, or keywords. The Boolean formula for the final search was (("deaf") OR ("hard of hearing") OR ("DHH")) AND (("children") OR ("child") OR ("kid") OR ("youth") OR ("minor") OR ("teenager")) [108].

3.2 Screening Process

Our initial search yielded 295 papers. After removing duplicates, 245 papers were included in the initial review stage. The lead author and one co-author screened the titles and abstracts of the identified papers. There were eligible: (a) primary and secondary studies reported fully; (b) papers published since 2000, (c) papers that directly aim or involved DHH children between 0-18 years old, and (d) papers on Human-computer interaction. On the other hand, exclusion criteria were the following: (a) papers that lacked peer review, (b) published in language other than English, (c) published as letters to the editor or conference abstracts; and (d) Grey literature (e.g., unpublished studies).

The initial criteria were determined before the screening process with reference to previous studies [71, 108]. In the screening process, authors would further discuss and refine the criteria collaboratively. At the same time, if one of the authors was not sure whether to include the paper or if two authors were in disagreement, we would meet with the other author to discuss the paper until a consensus was reached among all authors. At this stage, 191 irrelevant papers were excluded from the total of 245 papers. In the last screening step, we read the remaining 54 full-text papers to check for their eligibility. Also, to exclude bias in the evaluation, two authors independently evaluated the full content of each paper to ensure that the paper met inclusion and exclusion criteria previously mentioned.

In this final step of screening, seven papers were excluded because they were not technology designed for children, four were excluded because they did not provide enough information, and two papers were given the same case studies so only one was retained, finally 42 papers were included in our review.

3.3 Coding process

To answer our research questions, the lead author developed the initial coding set with reference to previous studies [71, 108], and after all the authors discussed and agreed on it, the four authors started the first round of coding with five (11.90%) representative papers from the corpus. After the first round of coding, all authors discussed the coding results and revised the coding set according to the coding process. To ensure consistency and accuracy of coding, four authors re-coded the five papers. At the end of coding, the average inter-rater agreement among the four authors was 85.6% by Holsti's method with a strong agreement [55]. Through further discussion, we collaboratively built the final codebook (Table 1). Subsequently, the remaining papers were equitably assigned to the four authors for final coding. If any uncertainties occurred throughout the process, they would be discussed. The lead author coded the remaining papers in a second round and reviewed the coders' corpus to ensure consistency and coherence in their coding.

4 Results

In this section, we describe the results of our systematic review. We report on temporal and geographical trends of publications, paper contributions and goals, research methods applied throughout the research process, and children's roles in research.

4.1 Temporal and Geographical Trend

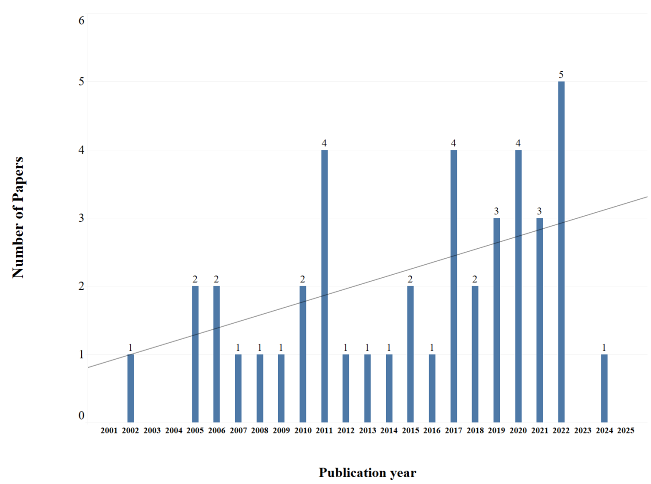

Figure 2: Number of papers by year of publication

Since 2000, the number of publications in HCI concerning DHH children has been increasing with an overall positive trend (linear

Table 1: The code categories in our corpus that correspond to our three research questions.

Category	Codes examples
RQ1:What are the research objectives, contributions, and technology types for DHH children within HCI?	
Contribution type	Theoretical, empirical and artifacts.
Research Objectives	Learning, assisted communication, social interaction etc.
Technologies type	PC or Tablet, mobile, robot, AI, VR etc.
RQ2: What design and research methods are used throughout the development process?	
Technics	Observation, brainstorming, focus group, interview, survey, workshop etc.
Design approach	user-centred design, participatory design, co-design, participatory action research/design etc.
Methods	Qualitative, quantitative, and mixed methods.
Experimental design	Experimental(including quasi-experimental),longitudinal,cross-sectional and non-experimental.
Duration	Length of participants' engagement in research
Number of participants	Total number of participants who complete research or include in data analysis
Context	School, family, lab, online etc.
Region	Country
Mixed group of not	Mixed hearing ability group, hearing impairment and other ability impairment group
Group activity or individual activity	Participants engaged in research are in the group or alone
RQ3: What is the role of DHH children in designing new digital technologies?	
Stakeholders	Parents, experts, caregivers, teachers, DHH children, hearing children
Children's role	Users, testers, informants, design partners
Age, SD and range	Children and Other stakeholders
Gender	Children and Other stakeholders: female, male and non-binary
Children's hearing impairment degree	Deaf, slight/moderate/profound hearing impairment
Children's language preferences	Oral language, Sign Language, Lipreading
Parents hearing ability	Hearing, deaf, slight/moderate/profound hearing impairment

regression: R^2=0.213,$p = 0.041$) (see Figure 2). The year 2022 stands out as the most productive, with 5 publications, mostly related to technology for sign language learning [96, 115, 120, 121], followed by 4 publications in 2011, 2017, and 2020. However, as of 2023, we did not find any publications, and by March 2024, only a single study have been published. Additionally, according to our data (see Table 2), the majority of research papers were published on the International Conference on Human-Computer Interaction (HCII), the SIGACCESS Conference on Computers and Accessibility (ASSETS) and Interaction Design and Children Conference (IDC) with 6, 4, and 4 papers respectively..

To analyse the geographical distribution of papers (see Table 3), we first checked the reported research region of these papers, and if not reported, we used the regional distribution of the authors' affiliation. The majority of the research published is held in Anglo-Saxon countries. The USA has the highest number of published papers (16 papers) followed by Australia with 4 papers.

4.2 Contributions, Objectives and Types of Technology

We systematically analysed each paper's reported contributions (empricial, artifacts and theoretical), research goals (e.g.: learning, assistive communication, social interaction), and types of technologies (e.g.: mobile, robot, AI) (Table 4).

4.2.1 Research contributions. We analyzed the contributions of the 42 papers in our dataset and categorized 20 research papers as empirical, 14 as an artifact, and 8 as theoretical [118]. The data indicate that most research in this field has focused on empirical contributions — i.e., new knowledge derived from observation and

Table 2: Venues distribution of papers

Venues	# of papers	References
HCII	6 (14.3%)	[11, 33, 34, 37, 39, 67]
ASSETS	4 (9.5%)	[16, 25, 115, 116]
IDC	4 (9.5%)	[15, 50, 58, 92]
CHI	3 (7.1%)	[38, 94, 102]
ACM SIGGRAPH	3 (7.1%)	[2–4]
OzCHI	3 (7.1%)	[66, 96, 97]
IJCCI	2 (4.8%)	[110, 114]
Other venues	17 (40.5%)	iiWAS [10],TEEM [12],CLIHC [40],SIGMIS-CPR [65],ICEDS [73],CHIuXiD [79],IVA [86],TALLIP [98],i-CREATe [120],ICMI [121],Media Architecture Biennale [36],ICLIQE [6],SAICSIT [1],KCESS [9],Interaccion [27],Ijim [81], IJHCI [29]

Table 3: References and geographical distribution of papers

Region	# of papers	References
US	16 (38.1%)	[2–4, 15, 25, 29, 33, 39, 50, 58, 86, 92, 102, 115, 116, 121]
Australia	4 (9.5%)	[65, 66, 96, 97]
Brazil	3 (7.1%)	[11, 34, 37]
China	3 (7.1%)	[73, 79, 110]
Mexico	2 (4.8%)	[27, 40]
Kuwait	2 (4.8%)	[9, 10]
Indonesia	2 (4.8%)	[14, 120]
Colombia	2 (4.8%)	[12, 38]
Other region	12 (28.6%)	Germany [16],Singapore [94],Austria [36],Namibia [1],Jordan [9],Chile [114], Mexico [27],Sri Lanka [98],Spain & Scotland [38],United Arab Emirates [81],Greece [67]

data collection — while contributions in the form of theory have been the least common. Considering the 20 research papers (47.6%) categorized as **empirical** contributions, the great majority (n=17) were concerned with evaluating tools to assist DHH children in learning language, communicative skills, literacy and mathematics, etc. Examples include supporting young DHH children's learning [1, 11, 37, 67, 81, 97] or development through Augmented Reality, interactive or wearable technologies [15, 79, 86, 110, 114] and movie captions [2, 40]. For instance, Bai and colleagues [15] found that Near-Object Projection (compared to Smart Glasses, Smart Watch, or Tablet) was the preferred choice for real-time delivery of ASL, and that haptic feedback was the best choice for improving parents' awareness of DHH children's attention, thus providing guidance for the future design of communication technologies that support real-time and context-aware communication in ASL. The remaining 3 empirical studies focused on DHH children's sensory experience [36], self-efficacy in learning [14], and on DHH chidlren's evaluation of different technologies [12].

Fourteen papers (33.3%) held their contribution categorized as an **artifact**, which includes research on technology design, developing new systems, architectures, tools, toolkits, techniques, sketches, mockups, and envisionments that reveal new possibilities, enable new explorations, facilitate new insights, or compel us to consider new possible futures for children with DHH. Among these, most artifacts (n=9) were developed for DHH children to learn sign language leveraging different technologies such as a kinect depth-mapping cameras for sign recognition [121], a multimedia dictionary [120], a robot or an avatar [98, 102], an interactive game [34, 50], gesture recognition game [25] and, smart toys [58, 92]. For instance, Huang et al. [58] designed an augmented teddy bear with a LCD screen to present ASL videos to DHH preschoolers. The other 5 artifacts were designed to assist communication (n=2)

Table 4: References and counts of papers for contribution, research objectives and technology type.

Category	References	# of papers
Contributions		
Empirical	[1, 11, 12, 14, 15, 36, 37, 39, 40, 67, 79, 81, 86, 94, 96, 97, 110, 114–116]	20 (47.6%)
Artifact	[2–4, 10, 25, 33, 34, 50, 58, 92, 98, 102, 120, 121]	14 (33.3%)
Theoretical	[9, 16, 27, 29, 38, 65, 66, 73]	8 (19.0%)
Research objectives		
Sign language learning	[4, 11, 25, 34, 50, 58, 81, 86, 92, 96–98, 102, 115, 116, 120, 121]	17 (39.5%)
Literacy learning	[27, 37, 38, 40, 114]	5 (11.6%)
Mathematics learning	[1, 3, 4, 110]	4 (9.3%)
Assisted communication	[2, 10, 15, 16]	4 (9.3%)
Educational assistive technology	[9, 29, 39, 67]	4 (9.3%)
Multisensory perception	[36, 94]	2 (4.7%)
Other	[12, 14, 33, 65, 66, 73, 79]	7 (16.3%)
Technology type		
PC or tablet	[1, 2, 4, 9–11, 14–16, 27, 33, 34, 37, 39, 50, 65, 67, 81, 92, 98, 115, 120]	22 (53.7%)
Mobile	[11, 81, 96, 97, 115, 116]	6 (14.6%)
VR	[3, 73]	2 (4.9%)
Avatar-combined-robot AI system	[86, 102]	2 (4.9%)
Other technology	[15, 25, 29, 36, 58, 94, 110, 114, 121]	9 (22.0%)

[2, 10], mathematics learning (n=2) [3, 4] and computer literacy learning (n=1) [33].

Lastly, 8 papers (19.0%) were classified as having a **theoretical** contribution, the least represented in our dataset. A theoretical contribution could include reflections on technology design for children with DHH, new or improved concepts, definitions, models, principles, or frameworks. Four papers had their theoretical contribution related to educational technology, describing guidelines for designing learning and teaching platforms for DHH children [9, 27, 29, 38]. Other four research examined the impact of Deaf culture on design [66], or assessed DHH children's expectations and attitudes toward technology [65], while others explored virtual reality technology in rehabilitation training [73] or virtual representations of real-world objects [16].

4.2.2 Research objectives. The main research focus is related to the development of technologies to support sign language learning (n=17/43, 39.5%, with one article containing two objectives). Most researchers provide videos of sign language to DHH children through educational games, One example is MySign [81], a mobile app that gamifies the learning of Arabic sign language. It displays pictures, Arabic words, and videos of sign language on the screen, allowing children to learn sign language step by step through game. Followed by 5 papers (11.6%) focused on literacy learning. As an example, a Spanish literacy web platform that provides children who are proficient in Mexican Sign Language and are taking basic Spanish courses with a platform that displays both LSM and Spanish and accommodates users with varying hearing abilities [40].

Meanwhile, four papers (9.3%) aims to support DHH children in learning mathematics, like AR app for DHH children provides more comprehensive information when solving mathematical problems and understanding abstract concepts, encouraging active learning in children [110].

Other four papers focused on assisting communication behaviours of DHH children, for instance, research on sign language subtitling of movies to assist DHH children who cannot read English and can only communicate through sign language [2]. Moreover, there are four papers on educational assistive technology, that is, how to better enhance the experience of using assistive teaching equipment in school [29]. Furthermore, the other 2 (4.7%) papers focused on multisensory perception in DHH children, Petry et al. [94] use visual and vibrotactile sensory devices to assist DHH children in perceiving musical rhythms.

Finally, the remaining studies focus on different topics, including the influence of hearing culture on technology design for DHH children [66], user experience evaluation for DHH children [12], collaborative learning for DHH children [79], computer science learning [33],web page captioning and self-efficacy for DHH children [14], DHH children's expectations from technology [65], and speech learning for DHH children [73].

4.2.3 Technology types. As shown in Table 4, the most common technology used was a PC or tablet (53.7%, n=22/41,with 4 papers included two types each and 4 with no technology), followed by a mobile phone (14.6%, n=6). In addition, two other papers (4.9%) used virtual reality (VR) environments to promote sign language mathematics learning [3] and speech training for DHH children [73]. Other 2 papers (4.9%) used an avatar-combined-robot AI system to support American sign language (ASL) learning for DHH babies [86, 102].

Additionally, nine papers 22.0%, adopted different technological approaches, such as machine learning for automatic sign language recognition [25], a tangible smart soft toy for sign language acquisition [58], a wearable plug-and-play music-sensory-substitution system [94], American sign language recognition with the Kinect [121], a media architecture installation [36], smart glasses and watch [15], AR for math learning [110], multimodal e-books [114] and multisensory teaching aids [29].

4.3 Design and Research Methods

To gain a comprehensive understanding of HCI design to support DHH children, this review examined their HCI design cycle [57], including the identification of needs, the design of technology, and its evaluation. We identified the following aspects to analyse: methodology, the context of use, number of participants, whether it was a mixed-ability group, and whether it was a group interaction. In our corpus (Table 5), We found that most of the research on HCI for DHH children focuses on system's evaluation (n=13/42,30.9%), followed by design of technology (n=8,19.1%), and least on identifying the needs (n=5,11.9%) of DHH children. Meanwhile, 12 papers (28.6%) involve more than one process: 9.5% (n=4) contained these three processes (assessing needs, design and evaluation), whereas other 9.5% (n=4) papers described the design process and evaluation of the technology. 4.8% (n=2) identified user's needs and the design of technology; two other papers (4.8%) described the process of identifying needs and the evaluation of the technology. Finally, 9.5% (n=4) of the papers did not involve any design approach. Therefore, there are 13, 18, and 23 papers for needs assessment, design techniques, and evaluation, respectively, and papers that involve more than one process are not analyzed separately.

4.3.1 Identifying users' needs and requirements. Among the 13 papers describing the process of identifying needs (Table 6), four used multiple methods to identify needs and two of them collaborated with adult stakeholders. One combined survey and observation methods [15], another combined online survey and interviews [114]. Two other papers used observation and interviews [39], or observations, interviews, and questionnaire methods [27], both in collaboration with children. When analyzing each method separately, we found that surveys or questionnaires were the most commonly used research methods, accounting for 7 papers. Among them, two papers targeted DHH children [9, 27], three targeted parents or teachers [15, 81, 114] and two targeted experts [38, 79]. Interestingly, there was a study that used online questionnaires with experts, using a scenario-based approach to analyse the roles and narrative descriptions of the DHH children's context, needs, goals, gathering requirements for developing the technology[79]. Followed by the observation method, as expected, all 5 papers targeted specifically DHH children [9, 27, 39, 66, 97].

Meanwhile, 5 papers used the interview method, 4 of them reported interviews with adult stakeholders; teachers [27, 94, 114] and parents of DHH children [115], and only one paper directly interviewed DHH children [39]. In addition, one paper used a cooperative inquiry approach by using a think-aloud and gesture think-aloud process to assess DHH children's needs and expectations when interacting with the prototype [65].

Regarding the research's context, we found that school and online were the predominant research contexts, with 6 and 4 papers, respectively. Two papers were conducted in a family setting [65, 115], and other two did not explicitly describe the context [66, 97]. Additionally, one paper conducted research in both family and school settings [65].

Futhermore, we also coded the number of participants reported. We found that the numbers ranged from 1 to 65, depending on the research method. The number of participants used in surveys had a mean of 37.43 (SD= 19.83, 26-65)[9, 15, 27, 38, 79, 81, 114] is generally greater than the number of participants using the observation method (Mean=13.5, SD=19.1, 6-65) [9, 27, 39, 66, 97] and interviews (Mean=20.67, SD=28.38, 2-42) [27, 39, 94, 114, 115]. Finally, few studies incorporate mixed-ability participants and group interactions with technology. Only two research papers included mixed-ability participants in the study, one with parents and teachers of mixed hearing abilities [15] and the other with hearing parents and children with DHH [115]. Meanwhile, 2 studies used group activity to interact with the technology [66], one of which had both group and individual interactions [65].

4.3.2 Designing technology. From the eighteen papers that adopted a design approach to develop technology (Table 7), we examined their methodological approaches, the extent of child participation, the reported number of participants, whether activities were carried out individually or in groups, whether groups included individuals with mixed hearing abilities and the contextual environments in which each study was conducted. Considering the design approaches, we found that seven research papers did not provide sufficient detail. Contrarily, the other eleven research papers explicitly mention their approach with the co-design approach being the most used approach in our corpus [40, 50, 66, 114] followed by, user-centred design [9, 96], user tests [58, 115] and two frameworks based design [11, 34]. We also analysed if children were

Table 5: The distribution of HCI life cycle

Process	# of papers & References
Identifying needs	5 (11.9%) [15, 27, 38, 79, 97]
Designing technology	8 (19.1%) [2, 3, 10, 25, 33, 40, 50, 96]
Evaluation	13 (30.9%) [1, 12, 14, 29, 36, 37, 67, 86, 92, 98, 102, 110, 121]
Identifying needs and designing technology	2 (4.8%) [9, 115]
Designing technology and Evaluation	4 (9.5%) [4, 11, 34, 58]
Identifying needs and Evaluation	2 (4.8%) [65, 94]
All three processes	4 (9.5%) [39, 66, 81, 114]
Not conduct actual studies	4 (9.5%) [16, 73, 116, 120]

Table 6: The distribution of study method, study context and respective papers for the 13 identifying needs papers

Study Method	# of Papers & References	Study Context	# of Papers & References
Survey	7 [9, 15, 27, 38, 79, 81, 114]	School	6 [9, 27, 39, 65, 94, 114]
Observation	5 [9, 27, 39, 66, 97]	Online	4 [15, 38, 79, 81]
Interview	5 [27, 39, 94, 114, 115]	Family	2 [65, 115]
Wizard of OZ	1 [65]	Not clear	2 [66, 97]

Table 7: The distribution of study method, study context and respective papers for the 18 designing technology papers

Study Method	# of Papers & References	Study Context	# of Papers & References
Co-design	4 [40, 50, 66, 114]	School	5 [9, 25, 33, 58, 114]
User centred design	2 [9, 96]	Family	1 [115])
Usability testing	2 [58, 115]	Deaf association	1 [40]
Framework based design	2 [11, 34]	Education program	1 [66]
Experts focus group	1 [4]	Not mentioned	10 [2–4, 10, 11, 33, 39, 50, 81, 96]
Not mentioned	7 [2, 3, 10, 25, 33, 39, 81]		

included in the design process and found that seven (7/18) studies involved DHH children specifically in testing or designing prototypes [9, 40, 50, 58, 66, 96, 114]. In contrast, one paper [115] involved parents in testing a sign language learning prototype while another research study included an expert focus group to design an immersive learning game for DHH children [4].

Regarding the number of participants, we found that only half of the research studies (n=9) reported this information. Those research studies employing a user-centred design (Mean=21.5, SD=29.0) [9, 96] had a larger number of participants compared with studies employing other methods, such as usability testing (Mean=8.5, SD=3.5) [58, 115] or co-design (Mean=8.25, SD=4.21) [40, 66].

Considering the participation or not of mixed abilities groups, only one paper [115] included a mixed hearing ability groups in their design. This study reported the design of a platform for hearing parents to learn sign language to aid their communication with their DHH child.

Regarding the context of the design research (Table 7), more than half (n=10) did not report that information. From those eight reporting the context, the school setting was the most prevalent one.

4.3.3 Evaluating Technology. When analyzing which research papers included an evaluation phase in their study, we found that more

Table 8: The distribution of study method, study & subjects design, study context and respective papers for the 23 evaluation papers

Category	# of papers & References
Study Method	
Qualitative	7 [39, 65, 66, 86, 98, 102, 114]
Quantitative	8 [11, 14, 29, 34, 81, 92, 94, 121]
Mixed	7 [1, 4, 12, 37, 58, 67, 110]
Not mentioned	1 [36]
Study design	
Experimental design	6 [1, 14, 81, 86, 92, 110]
Non experimental design	12 [4, 11, 12, 29, 34, 37, 39, 67, 94, 102, 114, 121]
Not mentioned	5 [36, 58, 65, 66, 98]
Subjects Design	
Within subjects	4 [12, 14, 86, 94]
Between subjects	1 [81]
Both	3 [1, 110, 121]
Not mentioned	15 [4, 11, 29, 34, 36, 37, 39, 58, 65–67, 92, 98, 102, 114]
Subjects context	
School	12 [1, 4, 12, 36, 37, 39, 58, 67, 92, 94, 110, 114]
Lab	3 [86, 102, 121]
Online	2 [11, 29]
Rehabilitation centre	1 [110]
Unfixed setting	1 [81]
Both online and offline	1 [14]
Not mentioned	4 [34, 65, 66, 98]

than half (n=23/43) included this information (Table 8). Then we categorized these twenty-three papers according to their evaluation methodology (qualitative, quantitative, or mixed methods), type of study design, subject design (e.g., within- or between-subjects), the context in which evaluations were conducted, the reported number of participants, and whether participant groups included individuals with mixed hearing abilities.

In terms of the methodology employed, one paper did not describe its evaluation approach [36], so we analysed the remaining 22 research papers. We found that all the three methods were commonly used, with a prevalence (n=8) for quantitative methodology (e.g., questionnaires, experiments) followed by qualitative (n=7) (e.g., interviews, case studies, etc., and (n=7) mixed (combining qualitative and quantitative methods). On the other hand, regarding the evaluation experimental design we found that five other papers did not provide information on this matter. From the remaining seventeen, the majority preferred a non-experimental design (n=12), followed by six papers employing an experimental design. Regarding these six studies, four [14, 81, 86, 110] were controlled studies, one [1] longitudinal and one[92] cross-sectional. To get details of the evaluation method, we coded between-subjects or within-subjects designs and the duration or process of the research; four papers reported that it was a within-subjects design, one was between-subjects studies and three used both within-subjects and between-subjects design.

Regarding the context of the evaluation, we also found that the school (n=12/23) was the primary location, followed by the lab (n=3/23), and two studies were online.It is worth noting that one study installed the app on children's personal tablets for them to test it for a week, which increased the ecological validity of the evaluation [81].

Considering the reported number of participants, five papers did not provide this information. From the remaining eighteen papers, 11 papers involved 3-30 children, Whereas the other seven studies involved 1-135 adult stakeholders. Regarding the inclusion of mixed hearing ability populations, we found that only four studies reported their inclusion to evaluate the technology. Two studies [86, 102] included hearing parents and DHH infants to assess the DHH infants' reactions to the sign language learning tool; and the other two to evaluate mixed hearing ability children's mathematics learning experience [4, 110].

Regarding the duration of the evaluation phase, only seven papers reported such information: 60 minutes [121], 2 weeks [1], and 7 sessions [94], 1 session [34, 110], and 1 week [11, 81].

4.4 Children's Roles and Stakeholders' Characteristics

To understand how HCI research involves DHH children in technology design, we examined their roles across all phases of the 42 studies in our corpus (Table 9). Specifically, we categorized their involvement as users, testers, informants, or design partners, following Druin's framework [35]. To further understand the different roles of children in research, we coded the age, gender (Male, Female, and non-binary), degree of hearing impairment (deaf, slight/moderate/profound), language preference (oral language, sign language, lipreading, etc), and parent hearing level reported in the studies.

4.4.1 Comparison of children's and adults' participation in research. Children can take four roles in a research study, with their involvement increasing progressively in the roles of **users**, **testers**, **informants**, and finally, **design partners.** As **users**, children participate in the research and development process by engaging with technology, while adults may observe, record, or assess their skills. When considering children as **testers**, they can test low-fidelity prototypes (e.g., paper sketches), high-fidelity prototypes (e.g., interactive, but not fully functioning), and fully functional technologies at each design iteration). The third role children can take is **informants** which means that children take part in the design process by sharing ideas and opinions with the design team and acting as consultants, making their contributions at key points of the design process. Lastly, the highest involvement of children in research is considering them **design partners** throughout the entire research process [57, 71].

Out of the 26 papers in our corpus that involved children ([114] in both Users and Testers), the most frequently reported roles were **users** (n=11) and **testers** (n=10). These were followed by **informants**, reported by five studies. Only one paper (n=1/42, 2.4%) included children as **design partners** a cooperatative inquiry design research that attempt to find ways to co-design with DHH children's (Table 9).

On the other hand, we observed that most papers (n=33/42, 78.6%) involved more adult stakeholders than children (26/42, 61.9%). To further explored which studies included both children and adult stakeholders, and analyzed them according to the varying roles children assumed in the research. Among the 11 studies featuring children as *users*, 10 (90.1%) also incorporated adult stakeholders, and five [38, 39, 58, 86, 96] of these involved multiple adult stakeholders. The stakeholders most frequently involved in the research were teachers (n=6) [36, 38, 39, 58, 86, 96], followed by parents (n=5) [39, 81, 86, 96, 102], researchers [58] or experts [38]. Considering the ten studies with children as *testers*, we found that 70.0% (n=7) of them also included adult stakeholders, with teachers being the most included (n=6) [1, 9, 27, 92, 94, 114], followed by experts [4, 114] and parents [92]. Of the five studies of children as *informants*, four (80.0%) included adult stakeholders: Deaf culture and language experts, user experience experts, and designers [40]; interpreters [50], and parents [65]. Notably, one study included more than one stakeholder, such as an educator, psychologist and sign language interpreter [114]. On the other hand, in the research study that included children [66] as *design partners*, they also included interpreters, experts, and parents.

4.4.2 Characteristics of child and adult participants. To understand the generalizability of the research implementation, we coded information on the age, gender, hearing loss severity, language preference and hearing status of the parents of the children, as well as the adult stakeholders.

At first, half of the papers (21/42) didn't reported the age of the DHH children. From the remaining 21 papers, DHH children ages ranging from 6 months to 14 years old as users[16, 39, 58, 81, 86, 96, 97, 102, 110], 3 to 15 years old as testers [1, 4, 9, 12, 27, 92, 114], 7 to 18 years old as informants [25, 40, 50, 65, 114], and 3 to 5 years old as design partners [66]. The minimum age of the informant children was relatively higher (4 to 6.5 years old) than those considered for other roles.

Regarding participants DHH degree, only 23 papers reported such information, from mild, moderate, severe to total bilateral deafness [1, 4, 9, 12, 14–16, 25, 27, 39, 40, 50, 58, 65–67, 81, 94, 96, 97, 102, 110, 114]. On the other hand, only twelve papers reported the children's language preference [4, 9, 12, 27, 40, 50, 65, 66, 92, 96, 97, 114] and the gender of the children participants (n=10) [9, 12, 27, 50, 65, 66, 96, 97, 102, 110], not to mention the hearing condition of the parents (n=3) [15, 66, 102]. Interestingly, almost all studies did not report relevant characteristics of details of adult stakeholders (age, gender, hearing conditions, language preferences etc).

Finally, it is worth noting that of the 16 studies that did not involve children in the HCI design cycle, 12 (75.0%) involved adult stakeholders (Table 9). Among these, 3 papers [15, 67, 98] reported the age and gender of the adult stakeholders, 3 [2, 15, 79] reported the degree of hearing loss, and 7 did not report any participant information.

5 Discussion

This paper provides a comprehensive review of the last 24 years of HCI research for DHH children. In this section, we address our research questions, outline implications for the future of the field, and critically examine prior research perspectives of disability, Deaf culture, and the role and needs of DHH children in the design of digital technologies.

5.1 Answering the Research Questions

HCI research with DHH children mostly focus on sign language learning (RQ1). Our review reveals several limitations

Table 9: The distribution of children's role and corresponding adult stakeholders

Children's role	# of Papers & References	Distributions of adult stakeholders
User	11[16, 36, 38, 39, 58, 81, 86, 96, 97, 102, 110]	10/11 (90.9%) [36, 38, 39, 58, 81, 86, 96, 97, 102, 110]
Tester	10 [1, 4, 9, 12, 14, 27, 92, 94, 114, 120]	7/10 (70.0%) [1, 4, 9, 27, 92, 94, 114]
Informant	5 [25, 40, 50, 65, 114]	4/5 (80.0%) [40, 50, 65, 114]
Design partner	1 [66]	1/1 (100.0%) [66]
No children	16 [2, 3, 10, 11, 15, 29, 33, 34, 37, 67, 73, 98, 115, 116, 121]	12/16 (75.0%) [2, 11, 15, 29, 34, 37, 67, 79, 98, 115, 116, 121]

regarding the focus and scope of the existing research. First, we show that while investigating digital technologies for DHH children is an emerging area of interest in HCI, it has remained limited and scarce over the past two decades. For the past 24 years, we have only found 42 publications; from those, only 14 papers in the top HCI venues (CORE A*/Q1). This result suggests that the potential of digital technologies for DHH children is still in its infancy and requires further exploration. Second, contributions in the field are mainly empirical (n=20), followed by artifacts (n=14) and theoretical (n=8). Surprisingly, 13 of 14 artifacts did not refer to any empirical or theoretical framework/support, suggesting limited evidence-based technologies and misalignment between HCI research and recent calls from disability studies of *"Nothing about us without us"* [30]. Third, we found that the primary focus of current HCI research is centred on sign language learning. From 42 reviewed papers, 15 focus on teaching sign language to children, and 2 on helping parents learn sign language [115, 116]. Additionally, eleven papers explore interactive technologies to support DHH children's learning other skills in areas such as mathematics [1, 3, 4, 110], music [94], computer science [33], and reading and writing spoken languages English, Spanish and Portuguese [27, 37, 38, 40, 114]. The remaining research explores various communication assistive tools such as sign language captioning [2]. Therefore, there is still a need for new tools that allow children with DHH to communicate with others and learn other subjects [78]. Fourth, regarding the types of technologies used, PC and tablets are the most common devices. This can be due to some papers (n=13) being 10+ years old when PC-based solutions were broadly adopted. Moreover, the inherently visual nature of sign language [8] can also play an important role, often requiring larger screens. On the other hand, there exists great research potential to explore smartphone and wearable devices as mainstream assistive technologies and offer DHH children the benefits of mobile technologies.

Research uses mixed methods with heavy reliance on hearing adults (RQ2). This section discusses our results on the research methods considered in designing, developing, and evaluating technologies with/for DHH children. Overall, prior work leveraged various methods throughout the design process and depending on the research goal.

For instance, 13 studies assessed DHH children's needs before any development of technology (Table 6) through surveys, questionnaires and interviews to collect data among stakeholders (e.g., teachers and parents) or a combination of observations and interviews when interacting with DHH children. Using quantitative and qualitative methods allowed researchers to gather relevant information for developing technology for DHH children.

The 18 papers that focused on technology design employed a variety of methods (Table 7). Six used co-design or user-centered approaches, prioritizing involving end-users in the design process to create more effective and user-friendly solutions. However, only four studies directly involved children with DHH through co-design practices. Moreover, only one work explored the broader social context of DHH children by accounting for mixed-hearing settings with DHH children and their hearing parents. Less frequently used methods included two usability tests, one focus group and two framework based design without participants.

Twenty three papers focused on evaluating designs (Table 8) by employing qualitative and quantitative methods (n = 15) more than mixed methods(n=7). Notably, half of these studies used hearing adults, such as teachers, parents, and interpreters as proxies to children, while the other half included hearing experts to support children during the study.

Despite these, a significant number of papers on DHH children lack critical information regarding methods and procedures. Of the 42 papers, 31 specified the number of participants, only half clarified ages (n=21), hearing impairment degree (n=23), and few reported children's language preference (n=12), gender (n=10) and parent's hearing condition (n=3). Seven did not describe the design method and sixteen did not include children in evaluation. This lack of detail poses challenges for research replicability and raises concerns about the rationale behind decisions in these studies.

Children mostly participate as testers and users while hearing adults act as informants(RQ3). Most work in the field used hearing adults as informants of children with DHH (n=17). Moreover, in twelve projects, hearing adults were recruited instead of children. Although we acknowledge the many advantages of using proxy stakeholders such as avoiding "user fatigue", we argue that children can have a unique and significant voice throughout the design processes and evaluation of new technologies. When children were involved in the research projects (n=26), their role was mostly passive acting as users, testers, or informants (n=25). Only one papers report giving higher levels of agency to children by involving them as designers.

The majority of studies were conducted in primary school settings with DHH children between 6 and 11 years old [4, 9, 12, 16, 50, 81, 96, 97]. Only five studies focused on infants and preschoolers, ranging from 6 months to 5 years old. These projects were conducted either in family or kindergarten settings [58, 86, 92, 102, 110].

Overall, the 42 papers report involving 253 children (74 males, 57 females, and 122 with unspecified gender). However, all studies involved small participant samples (fewer than 10 children), except one that included 42 primary school children from two different countries [9] and another on children with mixed hearing abilities [110].

5.2 Critical Reflection

In this section, we critically examine the findings of our review reflecting on the role of DHH children in the design of digital technologies, and how prior research views disability and Deaf culture.

Undervaluing DHH Children's Voices. Our corpus showed that DHH children's observations and interviews with adult stakeholders were the most common methods to identify users' needs. All observation studies were conducted with DHH children; most surveys and interviews were with adult stakeholders. Although observation is a common method in both HCI and psychology to inform technology design or understand children's cognitive development [31, 57], it can significantly limit DHH children's agency throughout the design process, which is in line with the challenges of designing with children with other disabilities [20, 106, 109].

DHH Children rarely have the opportunity to voice their views directly in the first person. When they do participate, it is usually through an adult serving as a sign language interpreter who can potentially impact *what* is being said and *how* is being said by both the children and research teams [64]. Furthermore, when children are solely observed or absent from these studies, the insights about their needs are gathered from a third-person perspective (researchers and adults), which risks misunderstanding and misalignments with children's lived experiences of the problems technologies could or should solve. Not having children directly express their voices can potentially lead to the development of irrelevant, difficult-to-use, and unappealing technologies [57]. Additionally, none of our corpus papers involved DHH children in determining the purpose of the technology development. Instead, these studies had pre-defined ideas and prototypes. DHH children were involved as users or testers of technologies with little control over what should be developed. While involving DHH children is an essential step toward fostering inclusion in HCI [107, 117], overlooking their real-life needs and preferences during the design process may compromise the relevance and adoption of the resulting technologies [26]. Accessibility researchers are increasingly calling for supporting the autonomy and agency of people with disabilities in the design process, to build creative environments that enable them to design digital technologies in ways that are more meaningful than force-feeding preconceived problems and "correctional" solutions [107]. It is also noteworthy that in the field of Child-Computer interaction, recent work is gradually moving away from expert to participatory design approaches and urging researchers to balance power dynamics and empower children in designing technologies for them [22, 71].

Disconnection between HCI Research and Deaf Culture. Article 6 of the Declaration on the Rights of Deaf Children, approved by the World Federation of the Deaf in 2021, affirms the fundamental right of DHH children to learn and use sign language and access Deaf culture *"All deaf children have a right to learn the linguistic identity and deaf culture"* [88]. While research suggests that DHH children's ability to navigate the differences between Deaf and hearing cultures is vital for improving DHH adults' ability to navigate the academic and professional world [43], most DHH children grow up disassociated from Deaf culture [101]; 90% of DHH children are raised by hearing families [80], with limited (or no) exposure to Deaf cultures and sign language usage [47, 47, 63]. Thus, building a linguistic and cultural identity in such contexts can be challenging [23].

While supporting DHH children to learn and practice sign language is key to achieving such goal [58, 86, 115, 116], Deaf culture is not limited to sign language. Deaf culture is visually centred and has unique behavioural patterns and epistemology [32]. For example, when Deaf people introduce someone, providing background details and sharing personal stories is acceptable and polite, or communicating with food in the mouth is not considered rude. Deaf people's attention-getting behaviours are based on the visual or motor sensory systems, and appropriate behaviours include, for example, tapping on shoulders, waving arms, and loud speech sounds; however, these behaviours are more or less unwelcome in hearing culture, and in some cases are even considered unacceptable by hearing society, which results in negative attitudes towards Deaf individuals [43]. DHH children, particularly those with hearing parents, can have few opportunities to learn about these behavioural patterns before adulthood; living with the scrutiny and prejudice of hearing culture can result in a range of mental health issues, influenced by low language fluency, inadequate knowledge base, and emotional, and behavioural disorders [46, 70]. Overall, most research in HCI has focused on individual sign language learning with limited research accounting for the sociocultural settings and challenges of DDH children.

5.3 State-of-the-art Gaps and Future Implications

Our research provides a general reflection on the gaps in previous research and on future digital technologies for children with DHH, offering potential applications in a variety of contexts and activities.

Build a DHH Children's-Centered Design. Involving children with disabilities as co-designers in a meaningful way is often challenging [54]; for instance, it takes time to build trust and there are several communication challenges to overcome. Researchers need to familiarize themselves with the Deaf culture, be aware of communication cues, and increase awareness of non-verbal communication [66]. Establishing a common communication channel through sign language or other methods facilitates fluid, informative, and effective exchanges between researchers and DHH children as design partners [64]. For future studies, we recommend that researchers immerse themselves in Deaf culture, gain a deep understanding of non-verbal communication, and ideally, learn the language used by the children they work with to enable fully independent dialogue. They also need to adapt new design methods when co-designing with DHH children to minimize the impact of communication and cultural challenges on children's active participation in design. This implication is in line with recent research on the education of DHH children [28], which argues for shifting to a Deaf-centered design, advocating for the integration of DHH researchers and epistemology in the design process, focusing on the characteristics of deaf students and identifying their needs.

Design for Incidental Interactions. Many DHH children face limited communication opportunities in their daily lives, particularly within family and school environments where the majority of individuals are hearing. For instances, in families, DHH children experience what is known as *"dinner table syndrome"* [49, 101], where they sit with hearing family members and are expected to participate in conversations they cannot fully understand. This lack of communication extends to mainstream schools, where most students are hearing [49, 101]. Such environments—both at home and school—limit opportunities for incidental learning and reduce DHH children's ability to develop into fully engaged members of society [49, 101]. Our review showed that sign language learning for DHH children is the main focus of current HCI research, which is highly important for their cognitive development [78]; fundamental to improve their literacy and their ability to understand the world around them [45]. However, it is essential to recognize that language acquisition in children involves intentional learning of words and grammar but also significant incidental learning [7].

Studies on sign language have found that DHH children exhibit different language characteristics when communicating with various people beyond classroom settings. Specifically, they use more diverse language, themes, and perspectives and display greater creativity when interacting with their friends [53, 84]. There is an opportunity to explore new technologies that enable DHH children to access and communicate with hearing people anywhere at any time. It is critical HCI designers consider incidental mixed-hearing ability interactions, which are fairly common in daily life, such as during playtime [85], school activities, or at home [49, 101]. Moreover, future interactive technologies must overcome the mobility limitations of PC and tablet-based solutions without sacrificing sign language expressiveness, such as rich facial expressions, and body language to convey different meanings, and intensity levels. Although several solutions showed the potential of using alternative mediums (e.g., a soft toy for sign language acquisition [58], wearable plug-and-play music-sensory-substitution system [94], and intelligent wearables [15]), they are still highly dependent on videos and avatars, that do not fully express the 3D perspective of sign language such as gesture intensity, and facial and body expressions [8]. As a result, there is still a critical need for HCI research and development of technologies that support early sign language learning and facilitate communication between the DHH community and hearing individuals in diverse environments. We envision that using novel interactive devices, based on ubiquitous technology (such as smartphones, and smartwatches), that are mobile and expressive can support the development of DHH children's communication skills and, more critically, timely acquisition of information, culture, and social skills by interacting and communicating within mixed-hearing ability groups, everywhere, and anytime.

Therefore, we as researchers, have a role to play in exploring how to provide communicational environments that facilitate incidental learning from an early age, such as during playtime [85] or at family time [49, 101] developing DHH children's sign language acquisition as well as allowing a shared communication platform for them to be fully included in mixed-hearing ability discussions.

Support DHH Children Build their Cultural Identity. Most DHH children have limited opportunities to engage with Deaf culture. Future researcher can leverage technology design to provide DHH children (parents and teachers) with the tools to navigate Deaf and hearing cultures, supporting their identity formation [23, 24, 91, 100]. These tools must be designed in ways that are both accessible and acceptable to Deaf children, ensuring meaningful adoption and use [91], exploration in an autonomous way. This approach should also examine the interplay between using assistive devices and the culturally defined identity formation of DHH individuals. It should prioritize the design of technologies that empower DHH children to navigate both Deaf and hearing cultures, ensuring that these devices are meaningful and useful not only for the DHH children's themselves but also for their hearing families, educators, and peers, fostering mutual understanding [100].

Need for Comprehensive Reporting on Children's Information. HCI research involving DHH children often omits critical information, including age, gender, degree of hearing impairment, language preference, and hearing status of parents. Twenty one papers (50.0%) in this review failed to report children's ages, limiting the pratical application of tools tailored to their developmental stages. Children's cognitive, social, and emotional abilities vary significantly across age, thus designing for a specific age group is critical to the effectiveness of the technology [22, 26, 71]. Meanwhile, gender as a critical influence on technology access, engagement, learning styles, and social experience [62, 69] which is often underreported in studies of children with DHH, weakens the generalizability and depth of the findings. Moreover, the degree of hearing loss and DHH children's language preference (monolingual or bilingual) significantly impacts cognitive styles and interactions with technology [83, 111]. Additionally, The hearing status of parents also plays a key role in development, as differences in parenting between hearing and Deaf parents can influence the cognitive development of children with hearing loss [104], making it important to consider in design. Therefore, we recommend that future research collect and report comprehensive information about DHH children. Additionally, consistent with research on children with ADHD, a standardized reporting framework should be established [108] to improve the technology's specificity and practicality while providing valuable reference data for subsequent studies.

Adapt Evaluation Processes to DHH Children . Our review showed that most studies used quantitative or qualitative evaluation methods, and only 30.4% used mixed methods methodologies. This result is much lower than the child-computer interaction studies with non-disabled children (37.9%) [71]. Combining multiple methods to capture user experience information is an important trend in HCI in recent years, quantitative measurement or qualitative depiction alone limits the understanding of users' real experiences and may even lead to the wrong influence [95]. For children, whose reasoning and cognition are still developing, this is even more the case. For example, using questionnaires alone restricts children from expressing emotions, thoughts and opinions, while using interviews alone is prone to obtaining diverging information [61]. Moreover, research has shown that experimental design is an effective tool for reliable interface design with a significant impact on results, conclusions, and replicability [42, 108]. However, in our review, only one quarter, six out of twenty three, of the evaluation papers conducted robust experimental design techniques, describing subject test conditions (within or between subjects), measuring times, and participant details. In addition, most of the contexts evaluated in our corpus are single settings (n = 16/23) and rarely evaluated over long-term (n = 3/23). To improve children's engagement and the sustainability of technology use, it is necessary to conduct across multiple contexts and over an longer term [107, 108]. Thus, conducting multiple methods of evaluation across DHH children's experiences with technology, experimental design, multiple field settings, and long-term evaluations is a way to increase the reliability and validity of research. Future evaluation research also needs to consider adapting or developing evaluation methods based on the needs of DHH children.

5.4 Limitations

To our knowledge, this is the first systematic review in the field of HCI, specifically focussing on research related to DHH children. It addresses a critical knowledge gap by providing insights into the current state of technology for DHH children and offering guidance on key considerations for designing and evaluating technology for this user group. Nevertheless, the literature review was limited to papers accessed through the ACM Digital Library and other top 20 HCI venues of Google Scholar, which includes a broad range of computing publishers and outlets representative of research in HCI, CCI, and Accessibility. We also acknowledge that designing technology to support DHH children involves multiple disciplines, such as disability studies, psychology, education, sociology, rehabilitation engineering, and others. However, to maintain alignment with our research questions focused on HCI, we decided not to include papers from these fields. Additionally, the codebook for analyzing our corpus was determined based on our research questions and standpoint; other researchers may generate different coding categories based on their research questions or framework.

6 Conclusion

This systematic review offers insights into recent advances in research on digital technologies for DHH children by analyzing 42 papers from the past two decades. Our findings reveal a significant focus on empirical research and artifact development, particularly in creating sign language learning software, with a predominant use of PC and tablet devices. Moreover, in terms of design and research methodology, needs assessment studies were mainly observational while questionnaires and interviews were primarily conducted with adult stakeholders; children were rarely directly involved in the development of technologies designed for them, and only 30.4% of the studies used mixed methods for evaluation. Moreover, DHH children were mostly involved as users and testers, and hearing adults were more involved in technology design and as a proxy for children's interests. To stimulate future research in this field, we provide a critical reflection on how researchers and designers can better address the actual needs of DHH children, ensure that they have an active voice in the design process, and foster their connection to Deaf culture as they grow up. Finally, we suggest implications for the design of future digital technologies, applied to various contexts and activities that support DHH children's development.

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