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Looking ahead: A systematic review of the research on AI-based applications for the deaf and hard of hearing (2000-2024)

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Abstract

This study aims to a systematic review of the latest applications of artificial intelligence (AI) for the Deaf and Hard of Hearing (DHH), including those with cochlear implants. The primary objective is to determine the areas of focus of AI applications and to identify trends in the research over the designated. The review was conducted using the Academic Research Library of the Saudi Digital Library and Google Scholar. The study covered peer-reviewed articles published during the years 2000–2024. 45 articles were iden-tified. The analysis revealed five primary areas of focus in the existing literature: (a) improve the function of hearing aids and/or cochlear implants (n = 17), (b) sign language translation (n = 13), (c) detect and predict hearing loss (n = 10), (d) enhance academic achievement and performance (n = 4), and (e) the ethics of the use of AI applications (n = 1). It was determined that there has been a marked change in the nature of research topic areas, as well as a significant (86.96%) increase in such studies in the last years (2017–2024). This review highlights the need to bridge the research gap regarding the psychological, social, and academic aspects of such technology on the population of DHH.From a practical perspective, this review provides valuable insights for policymakers, educators, and technology developers by highlighting priority areas for future AI solutions. The findings can be practically applied to guide the design of more inclusive educational programs, enhance rehabilita-tion strategies for cochlear implant users, and inform the development of ethical and DHH community-centered AI applications.

Keywords: Artificial intelligence (AI), Cochlear implants, Deaf or hard of hearing (DHH), Hearing loss.

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1. Introduction

In the past few decades, a great deal of progress has been made regarding the incorporation of technology into virtually all aspects of our daily lives. Included in these advancements are a diversity of assistive technologies to support individuals with disabilities, including those who are Deaf or Hard of Hearing (DHH). For this population, such technology can offset hearing impairment, communication difficulties, and other challenges. These technologies—which have become smaller as well as more portable and affordable—include wearable and wireless devices, virtual reality, augmented reality, robotics, and artificial intelligence (AI) [1]. This review focused on AI, which is defined as the simulation of human intelligence by machines, especially computer systems [2]. These technologies can be used for visual perception, speech recognition, decision-making, and language translation [3]. Part of the process of creating AI systems involves teaching computers how to think and learn [4].

Specifically, in the context of the DHH, which includes those individuals with cochlear implants (CIs), AI can play an important role in breaking down barriers to communication between the DHH and the hearing, which can support the former population's social integration. Recent developments in sensor technologies and AI algorithms are of particular interest [5, 6]. For many DHH people, AI offers a transformative potential, particularly through voice recognition and translation services, which open up new opportunities for more inclusive educational and workplace environments. AI advancements are also enhancing assistive technologies, including AI-powered hearing aids and cochlear implants, as well as tools for automatic speech recognition and natural language processing in both spoken and signed languages. In education, AI-driven tools such as interactive learning platforms, real-time transcription, and translation features for sign language-enabled by innovations like smart gloves and live sign language imagery- are improving accessibility and enhancing learning experiences [7].

Innovations in AI that support the DHH are also relevant to the special education sector, particularly given that many laws now specifically promote the provision of assistive technology to persons with disabilities, stating these tools and services represent key developmental benefits (e.g., Individuals with Disabilities Education Act Amendments of 1997; United Nations Convention on the Rights of Persons with Disabilities [UNCRPD] [8, 9]. Articles 9 and 21 of the UNCRPD state that governments are required to provide access to information and communication for people with disabilities.

In spite of these types of directives and guidelines, the possibility for those with disabilities to benefit from assistive technology is conditional on how well it is integrated into the curriculum and whether teachers are properly trained in how to implement it properly [10]. On a similar note, the World Federation of the Deaf ([WFD] has established that the deaf benefit from the use of technology and the Internet, also noting that information and communication across all areas of life should be accessible via sign language interpreting, subtitling, and/or closed captioning [11].

For the purposes of this review, the term "DHH" will be correctly used to include those who have cochlear implants; however, when reviewed articles only focused on the use of CIs this will be made clear.

There are many applications of AI for the DHH and particularly for those with CIs, as breakthroughs in technology have allowed for the development of apps that help these individuals learn, support better DHH instruction, and allow for the translation of sign language; some of this technology has incorporated machine learning to enhance sign language recognition [4, 12]. Parton emphasized how research has been steadily progressing in terms of the use of AI techniques to recognize and present sign language [6]. An important area of exploration in AI technology focuses on applications that reduce background noise in different environments to enable the hearing-impaired to better perceive speech; these apps involve the incorporation of software algorithms that automatically change settings based on the noise levels of the given environment [13-15]. Improving the ease with which DHH individuals can use hearing aids is also an area where AI has made great contributions [16-18]. In addition, AI has been used to significantly improve the quality of cochlear implants as well as to reduce the rehabilitation time for recipients [19-22]. However, although AI-dependent assistive technology is becoming more widely available, there has been little research regarding the ethics and implications of the use of these technologies to the DHH population [23].

2. Research Questions

RQ1. What areas are focused on by the identified research regarding AI applications for the DHH, including those with cochlear implants?

RQ2. Has the research on the use of AI to support the DHH changed over time in terms of frequency of publications, target area of AI application, and methodology?

3. Methods and Materials

3.1. Research Design

As stated, the study involved a systematic review of the literature dealing with the application of AI related to DHH, including those with cochlear implants. For guidance on the structure and format of systematic reviews, the updated Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) was referenced [24]. The data set consisted of studies presented in peer-reviewed scientific publications from 2000–2024. Google Scholar and the Academic Research Library of the Saudi Digital Library—the latter of which allowed access to the databases of AraBase, AskZad, EduSearch, Ebesco, HumanIndex, IEEE, Web of scince, and Sage—were utilized. The search was originally conducted on Feb 11, 2024. (The sources were last searched on September 9, 2025, as part of the process of reviewing and confirming the data for the purposes of submitting the work for publishing.) The data was logged using tables created in Microsoft Word for ease of processing and to facilitate the sharing of data for independent review.

3.2. Keywords and Inclusion/Exclusion Criteria

The content search term for the study was "artificial intelligence" or its accepted abbreviation of "AI." The sample search terms established for this study were: "deaf," "hard of hearing," "hearing impaired," "cochlear implants," "hearing difficulties," "hearing loss," and "otology"—each of which was separately searched with the term artificial intelligence. The inclusion criteria were:

1. Studies that focus on any one or any combination of the following: the deaf, the hard of hearing (HoH), the deaf and hard of hearing (DHH), those with cochlear implants, those with hearing impairment, those with hearing loss, and/or those with hearing difficulties.
2. The term "artificial intelligence" or "AI" is stated in the title of the article.
3. The research/study involves an application of AI to any of the populations stated in the first criterion that provides direct benefit to these individuals.
4. Peer-reviewed articles that appeared in referred/peer-reviewed scientific publications.
5. Articles published during the 2000–2024 time period.
6. Full text of the article is available.

Articles published before 2000 and articles with a publishing date after 2024 were excluded, as were articles that did not contain "AI" or "artificial intelligence" in the title. Similarly, if an article did not involve an application of AI that clearly supports and/or benefits the population(s) of interest it was excluded. Editorials, dissertations, and these were also excluded. (see Table 1 for the data extracted from each of the 45 studies). The PRISMA checklist was followed throughout the paper.

Table 1.
Summary of the data obtained from a systematic review of the literature on artificial intelligence in application to the population of the deaf and hard of hearing: 2000–2022.

	Author/s- Study	Year	Target group	Target Area	Country
1	Flynn and Lunner [14]	2005	DHH	A	Denmark
2	Parton [6]	2006	D	B	United States
3	Issa [25]	2009	D	D	Saudi Arabia
4	Shabana, et al. [26]	2013	DHH	A	Egypt
5	Aliabadi, et al. [16]	2015	DHH	C	Iran
6	Wathour, et al. [21]	2018	CI	A	Belgium
7	Kafle, et al. [23]	2019	DHH	E	United States
8	Jiang, et al. [27]	2020	D	B	China
9	Manoj Kumar, et al. [28]	2020	D	B	Sri Lanka
10	Meeuws, et al. [20]	2020	CI	A	Belgium
11	Oyeniran, et al. [4]	2020	D	B	Nigeria
12	Wathour, et al. [29]	2020	CI	A	Belgium
13	Waltzman and Kelsall [22]	2020	CI	A	United States
14	You, et al. [2]	2020	DHH	A-C	Canada
15	Umashankar, et al. [15]	2021	DHH	A	India
16	Wen, et al. [30]	2021	D	B	Singapore
17	Abd Ghani, et al. [31]	2021	DHH	C	Multiple (Funded by Basque CountryGovt.)
18	Balling, et al. [13]	2021	DHH	A	Denmark
19	Bhargav, et al. [12]	2021	D	B	India
20	Fabry and Bhowmik [32]	2021	DHH	A	United States
21	Papastratis, et al. [5]	2021	D	B	Greece
22	Rahme, et al. [33]	2021	DHH	A	Canada
23	Lee, et al. [34]	2022	DHH	C	Republic of Korea
24	Levin, et al. [19]	2022	CI	A	Russia
25	Madahana, et al. [35]	2022	DHH	A	South Africa
26	Ngombu, et al. [36]	2022	DHH	C	United States
27	Padmanandam, et al. [37]	2022	DHH	B	India
28	Schindler, et al. [38]	2022	DHH	D	Germany
29	Sankari, et al. [39]	2023	DHH	C	India
30	Wathour, et al. [40]	2023	CI	A	Belgium
31	Abousetta, et al. [41]	2023	CI	A	Egypt
32	Nugraha, et al. [42]	2023	DHH	D	Jakarta
33	Adão, et al. [43]	2023	D	B	Portugal
34	Maghawry [44]	2024	DHH	D	Egypt
35	Aliyeva, et al. [45]	2024	CI	A	USA + Istanbul (Türkiye)
36	Essaid, et al. [46]	2024	CI	A	Algeria- Qatar- UAE
37	Carlson, et al. [47]	2024	CI	A	USA
38	Kassjański, et al. [48]	2024	DHH	C	Poland
39	Li, et al. [49]	2024	DHH	C	Taiwan

	Author/s- Study	Year	Target group	Target Area	Country
40	Madahana, et al. [50]	2024	DHH	C	South Africa
41	AlSamhori, et al. [51]	2024	DHH	C	Jordan- Hungary- Georgia - Qatar
42	ZainEldin, et al. [52]	2024	D	B	Egypt - Saudi Arabia
43	Siddiqui, et al. [53]	2024	DHH	B	Pakistan
44	Sheng, et al. [54]	2024	D	B	Australia
45	Desai, et al. [55]	2024	D	B	Italy

Note: Group Area: (DHH) Deaf and hard of hearing, (D) Deaf, (CI) Cochlear implant.
Target Area: (A) Applications to improve the function of hearing aids and/or cochlear implants.
(B) Applications for sign language translation.
(C) Applications for detecting and predicting hearing loss.
(D) Applications for enhancing academic achievement and performance for people with special needs.
(E) Ethics of using AI applications.

3.3. Data Analysis and Article Retrieval

The search and screening processes were reviewed independently by two colleagues of the author with expertise in special education and/or academic research. One is a native Arabic speaker, and the other is a native English speaker. When either of the independent assessors indicated a differing opinion on the rejection/acceptance of an item, the item was reviewed by all three parties to determine the correct dispensation of the work.

3.4. Testing the Reliability

The reliability of the selected studies was verified by presenting them to two reviewers to provide a critical evaluation of the studies included in the systematic review and their achievement of quality standards. The reviewers agreed on the suitability of the included studies and these studies fulfill the specific criteria for inclusion and exclusion.

4. Results

4.1. Results for the First Question :What Areas are Focused on by the Identified Research Regarding AI Applications for the DHH, Including Those with Cochlear Implants?

Initially, 258 studies were identified through this search process. The process of obtaining the final sample of studies is presented in Figure 1. After these steps were taken, 45 studies remained. When there was any doubt about whether a study qualified for inclusion, the study's title and abstract were read, and a determination was made regarding whether it should be included.

4.1.1. Data Extraction

After determining the study sample of 45 articles, data were extracted from each, including: author name(s), year of publication, title, study objective(s), target area of the technique used, the methodology, and the major finding. One of the goals of this systematic review was to determine if publishing on AI in the context of the DHH has changed over the time period established for the study. Therefore, the 45 articles were divided into three time periods based on their years of publication: (a) early efforts (2000–2008), (b) emerging efforts (2009–2016), and (c) current efforts (2017–2024). Based on the analysis of the studies, it was established that there has been a noticeable increase in the publishing of articles on AI applications for the DHH in the past decade. The other goal was to determine if there were common areas of investigation in the research regarding the DHH and artificial intelligence.

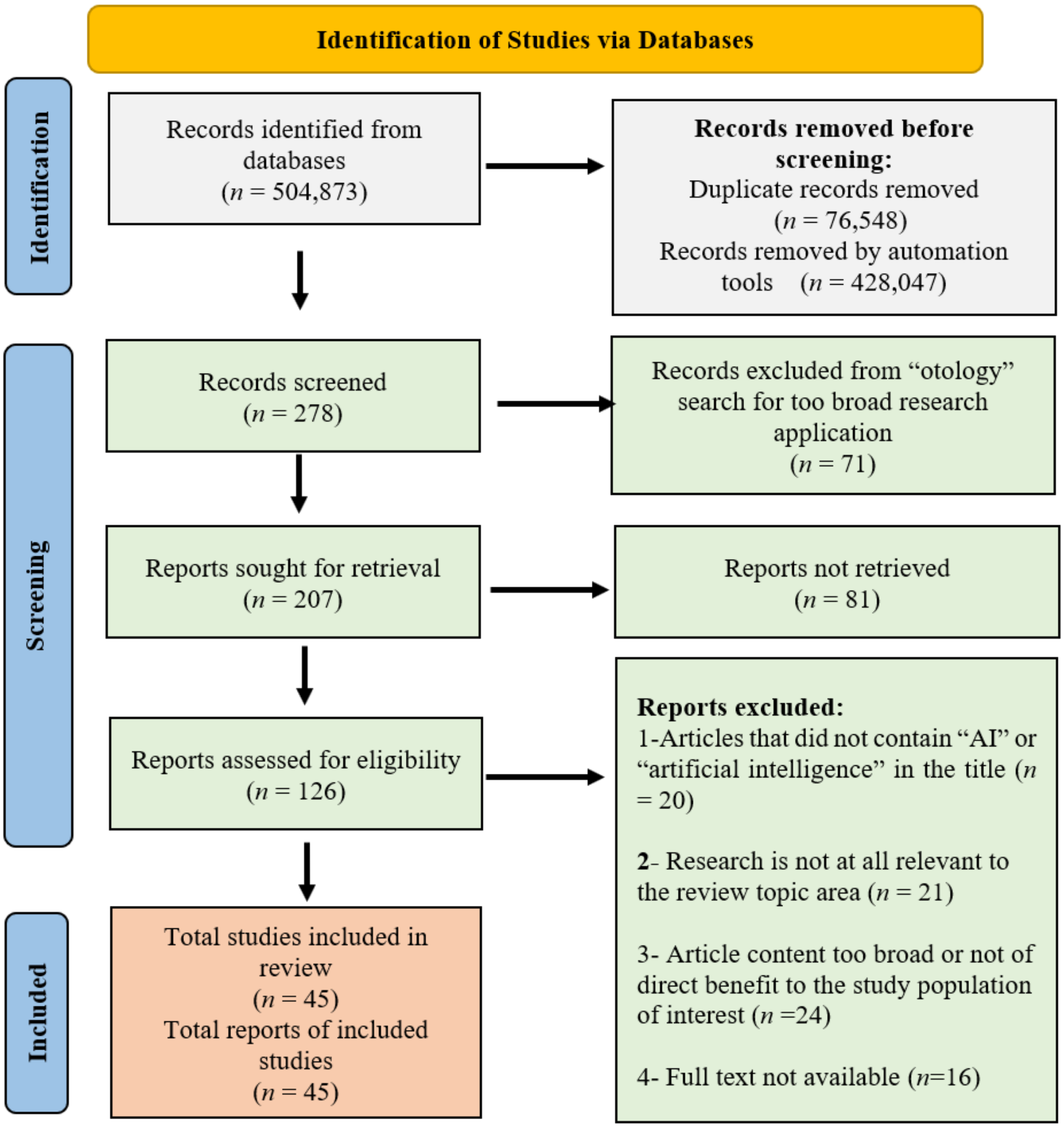

Figure 1.
Flow chart on the process per PRISMA adapted from Page, et al. [24].

4.2. Identification of the Themes

The following categories of AI application were identified: (a) improving the function of hearing aids and/or cochlear implants (*n* = 17; 38%); (b) sign language translation (*n* = 13; 29%); (c) applications to detect and predict hearing loss (*n* = 10; 22 %), which included an article that combined detection, prediction, and improvement of hearing aids (this article was consistently counted in the detection category); (d) improvement of academic achievement (*n* = 4; 9%); and (e) the ethics of using AI (*n* = 1; 2 %).

4.2.1. Improving the Functioning of Hearing Aids and/or Cochlear Implants

In this topic area, 17 studies were identified, including studies on: (a) development of software applications and systems using AI to improve the function and fitting of cochlear implants (e.g., [19, 21, 22, 29, 40] and hearing aids [14, 26, 33]; (b) analytical efforts to improve the function of hearing aids by reducing background noise [51]; (c) the use of AI in developing hearing aids and cochlear implants [15, 19]; (d) the role of AI in predicting eligibility for cochlear implantation [41, 47]; and (e) enhancing Postoperative Cochlear Implant Care with AI (ChatGPT-4) [45]. These studies employed empirical and analytical approaches; there was also a systematic review [46]. Meeuws et al., incorporated questionnaire into the analysis of their self-testing procedure with adult recipients of CI [20]; Flynn and Lunner also administered a questionnaire to their participants to obtain additional information on their preference for the AI-enhanced hearing aid being tested over the participants' existing hearing aids [14].

4.2.2. Sign Language Translation

Thirteen studies were identified that focused on applications of AI for use in sign language translation, which included incorporating a virtual sign language interpreter into written and audio texts (e.g., [28], smart sensor (data) gloves for sign language prediction [30, 47], the prediction of text pattern in sign language [12], and the conversion of speech into sign language [4, 5, 56]. And using video to translate speech to and from sign language [53]. And exploring Synergies between

Predictive and Generative AI-Based Strategies towards Sign Language Interpretation [43]. and the role of AI in empowered Auslan learning [53]. In addition, an article [27] that examined Chinese Sign Language innovations employing AI was identified, and a work by that involved a systematic review of the use of different AI methods for sign language rendering was located. While the study [52] conducted a review of artificial intelligence, deep learning, and machine learning in facilitating deaf and mute communication. The study [38] focused on systemic biases in Sign Language AI research. These studies involved empirical and analytical approaches as well as systematic reviews of literature.

4.2.3. Detection and Prediction of Hearing Loss

Ten studies targeting detection and prediction of hearing loss were identified, most of which involved examining the role of AI in this process [16, 31, 34, 39, 44, 51]. One study in this category was a systematic review of the literature on applications of AI to diagnose middle ear infections [46]. The study [2] focused on the latest AI techniques in otology to predict hearing loss, improve hearing aids, and develop speech. While the study [50] focused on development of an artificial intelligence based occupational noise induced hearing loss early warning system for mine workers.

4.2.4. Academic Achievement

The four studies located on applications of AI in relation to the academic performance and achievement of the DHH focused on mathematical and Langouge skills. One proposed a model for employing e-learning in developing some mathematical concepts for the deaf through AI [25]; the other employed AI to determine whether DHH students differ from their hearing peers regarding achievement and challenges in mathematics [48]. While the other two focused on the impact of using artificial intelligence on language skills such as improve reading comprehension [34] and teaching English language [42].

4.2.5. Ethics of AI Use

Only one study was found that examined the ethics of using AI to support DHH [23].

4.3. Results For the Second Question: Has the Research on the Use of AI to Support the DHH Changed Over Time in Terms of Frequency of Publications, Target Area of AI Application, and Methodology?

One key finding of this systematic review was that there has been a substantial increase in the published scientific studies on the applications of AI for assistive technology to support the DHH in the most recent period of the study, especially in the last 5 years (2020–2024) (see Figure 2). During the first period (2000-2008), only two studies were located; then, only three relevant studies fell in the second period (2009-2016). However, there was a dramatic rise in publications during the third period (2017-2024), in which 40 studies are found, comprising 89 % of the total number of studies identified in the review. As for the methodology used, again, this changed over time. For example, the studies that employed experimental and quasi-experimental methods increased in the last period. As for studies in Arabic that were part of the final study sample, only two were identified: [25, 34].

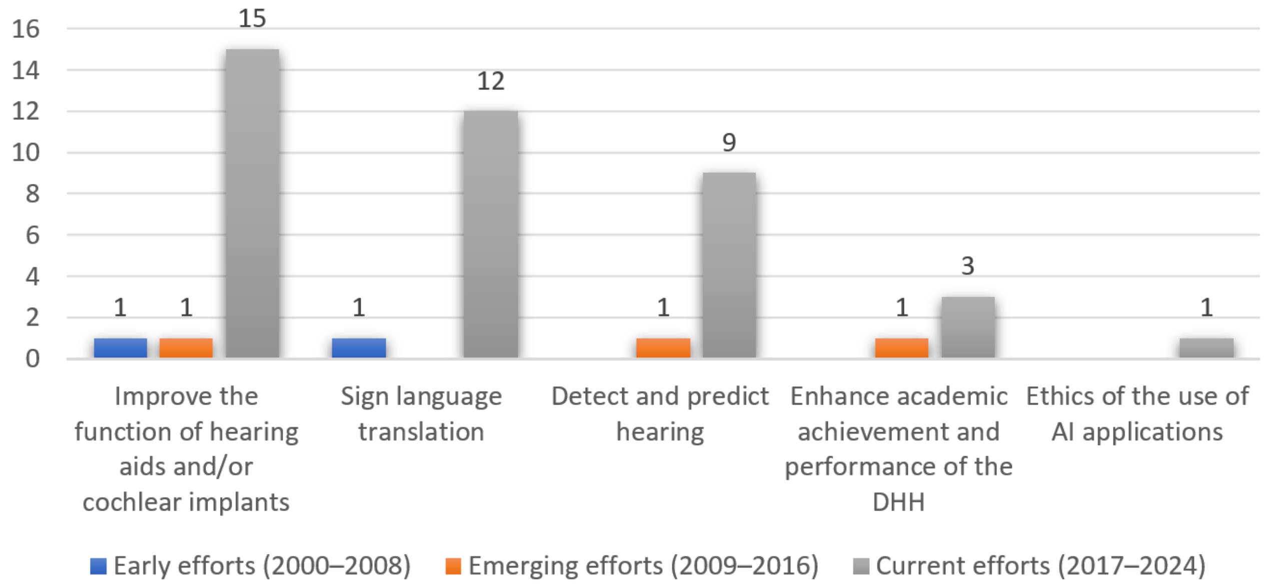

Figure 2.
Graphic presentation of distribution and characteristics of articles.

5. Discussion

The current systematic review shows that scientific studies of AI applications for DHH, including those with CIs, have focused on several areas. Globally, the majority of the roughly 70 million deaf individuals in the world use signed language for communication with each other and with their hearing family members. Given this statistic, broadening the ability of the DHH to communicate with the hearing via sign language is key to their social inclusion and integration [57]. Therefore, it was not surprising that a substantial percentage of the studies dealt with applications for translating sign language. Hence, research such as [4], which examined the application of AI for the recognition and interpretation of sign language, is of great importance. In the study [6], many different types of AI were covered, including robotics, virtual reality, neural networks. These different types of AI can have profound impact on the ways in which the DHH communicate and learn.

As a result, there is an urgent need to develop a reliable system for automatic sign language recognition [52]. Nevertheless, recent advancements in AI and machine learning offer promising potential to improve and expand these technologies [5]. Growing research in sign language recognition, generation, and translation AI has been ac-companied by calls for ethical development of such technologies. The advent of new artificial intelligence (AI) methods has ushered in cutting-edge strategies to address the limitations and difficulties associated with traditional signal processing techniques dedicated to Cis [46].

The largest number of studies (*n* = 17) dealt with improving hearing aids and cochlear implants. With the improvement in the technology, there has also been a related increase in the need to integrate machine learning algorithms into hearing aids to address issues such as background noise and information processing times [15, 26, 32, 50]. As the technology evolves and becomes more user-friendly, it is important that the independence of the DHH is maintained. Some research focused on reducing the need for repeated visits to medical/technical professionals for adjustments and training, which can be achieved through built-in machine learning that is based on DHH user preference and AI programming that better predicts appropriate hearing aid and CI settings [13, 20].

The identified studies that focused on cochlear implants were primarily aimed at improving the benefit of CIs using AI in the context of improving recipients' understanding of sounds and speech. The study [29] achieved mixed results in a case study involving two CI recipients. However, the findings were strong enough to assert that incorporating "AI-proposed adaptations" could have positive benefit in terms of improving recipients' word recognition at both ends of the sound level spectrum. Overall, machine learning techniques are expected to provide new solutions in the field of speech signal processing that also in turn can play an important role in increasing the acceptance and consideration of different hearing assistance technologies in different populations. AI has also been found to significantly improve the quality of CIs and to reduce rehabilitation time [19-21, 29].

While less frequent, a few studies identified AI as a method for predicting the complex phenomenon of hearing loss, including the use of artificial neural networks (ANN), also referred to simply as "neural networks" [15]. This was also the focus of the study [58], which compared and contrasted methods for assessing sensorineural hearing loss using ANN versus using backward elimination logistic regression, finding that both methods were successful. These results contrasted with those of the study [59], which found ANN to be more accurate than regression models for predicting hearing loss in the case of noise-exposed steelworkers. However, no single machine learning algorithm has been consistently identified as having the best predictive ability [2].

Some studies have noted that DHH students face added academic difficulties related to their disability, generally citing their language competence, particularly in reading, writing, and communication with others [60, 61]. However, research has also found that DHH students highly proficient in sign language outperform their DHH peers with lesser ASL proficiency across academic disciplines [62]. This further emphasizes the need for AI applications that improve the ability of signers to be understood by the hearing, allow for spoken language to be easily translated into sign language. In this review, the least examined area of study was that of employing AI in the context of the academic achievement of the DHH, where only four studies were located, all of which focused on this application in the area of mathematics and language skills. DHH students often show significant difficulties in the subject and tend to lag in their mathematical development as compared to their hearing peers [63]. This is attributed to different causes, including limited learning opportunities due to less accidental exposure to numerical ideas and delays in language and speech development. Santos and Cordes associated greater math lag in DHH children who were not exposed to sign language from birth [64]. Moreover, the development of early mathematical skills and their role in the difficulties DHH students tend to exhibit have not been adequately explored. For example, one of the two studies identified, Schindler et al., found that a factor commonly associated with math underachievement in the general population is not a trait of DHH students, who were found to outperform their hearing peers in such processes [48].

For regarding language skills, the American Speech-Language-Hearing Association (ASHA) identifies four main areas impacted by hearing impairment: delayed development in receptive and expressive language, communication skills, and academic challenges, including delays in academic achievement, social isolation, a poor sense of self, and limited opportunities for employment [65]. Several studies have shown that children with hearing impairments tend to have lower reading comprehension levels compared to their hearing peers [62, 66, 67]. A number of studies have explored how AI-driven learning strategies could potentially improve reading comprehension skills [23, 68]. AI plays a crucial role also in teaching English by providing personalized instruction that makes learning more engaging and helps students stay focused [42].

This points to the need for more research on the use of AI applications to improve not just DHH academic achievement but also DHH social integration. It is notable that most of the identified studies focused on sign language translation, post-surgery CI rehabilitation, improving the work of hearing aids and cochlear implants, and detecting and predicting hearing loss, whereas AI applications were not frequently examined in terms of significantly improving psychological or social aspects of the DHH. In fact, only two studies discussed achieving social integration through sign language translation and only did so indirectly [5, 12]. This indicates a need for more research on the incorporation of AI to facilitate the inclusion of the DHH. These innovations support DHH integration, create positive perceptions of the population to the hearing, improve DHH self-efficacy, and aid in the growth of DHH identity [69].

Research in AI applications relevant to the entire DHH population was found to be very limited in Arab countries compared to what is being conducted in other regions of the world, with only [25, 34] being identified in this review. This highlights the great need for expanded research in Arab countries. However, these findings also indicate that it may not be possible to generalize the findings of studies conducted in the developed world to the context of the DHH in developing countries, including Arab countries, due to different environmental conditions and personal characteristics that affect the characteristics of the DHH. McIlroy and Storbeck found that language, culture, and societal attitudes greatly affect the socialization of the DHH [56].

As for the methodologies used, the most common were experimental or quasi-experimental methods, after which came literature review. This is attributed to the great importance of the use of experimental methods to obtain accurate results regarding new innovations, such as the AI applications examined in this review [70].

When tracking the changes that occurred in the studies under analysis over time, the most notable factor was the rate of publishing during each of the three periods, and the fact that the proportion of studies in the last period is (89 %) of the total studies identified. This is a very large increase that may be due to the current trend towards the investigation and development of AI applications and their importance to quality of life [2, 16].

No matter how advanced AI technology becomes in the future, it's important for educators and professionals in deaf education to recognize that relying too heavily on AI could undermine the value of learning and exploration for deaf and hard-of-hearing students. Therefore, the focus should be on how these innovative technologies can best support these learners, helping them benefit from AI without sacrificing access to quality education, language development, identity, or cultural values. One effective approach to achieving this is by involving deaf and hard-of-hearing individuals in the design and testing phases of AI technologies. Additionally, it is essential to ensure that deaf and hard-of-hearing students are equipped with an education that prepares them for careers in STEM fields and industries [7].

Recent research underscores the crucial need to examine cultural and regional biases in AI systems designed for sign language applications, especially for Deaf and hard-of-hearing students. One systematic review highlight that "the majority of sign language AI research overfocuses on addressing perceived communication barriers, relies on non-representative datasets, uses annotations lacking linguistic foundations, and builds on flawed models… the field must make space for Deaf researchers to lead the conversation in sign language AI." [38].

In contexts involving Arabic Sign Language (ArSL), advancements are often measured purely by high recognition accuracy without addressing cultural or linguistic nuances. For example, one study reports that "using transfer learning with transformer-based and CNN architectures recognition accuracies reached 99.6% on the dataset, surpassing previous benchmarks and promoting inclusivity in Arabic-speaking Deaf communities." [71]. However, another critical review notes that research on Egyptian Arabic Sign Language (EASL) remains scant, emphasizing that "EASL combines elements of Modern Standard Arabic, Egyptian dialects, and regional sign variations... current literature lacks dialect-specific datasets and alignment techniques, creating significant gaps in developing inclusive, culturally relevant recognition systems for Deaf Egyptians." [72].

In addition, the integration of AI and connectivity in smart hearing aids introduces significant ethical concerns, particularly regarding data privacy, algorithmic opacity, and user autonomy. Smart wearables are increasingly capable of collecting users' movement data to deliver personalized services. Nevertheless, the storage of such data raises notable privacy concerns among consumers. Consequently, when determining whether to integrate this functionality into their products or avoid it, managers must weigh the potential backlash stemming from customers' strong privacy sensitivities. Previous research has indicated that the recurring benefits of smart products—such as enhanced convenience in managing daily routines—can sometimes offset privacy concerns [73].

Moreover, a broader review of ethical challenges in smart healthcare technologies emphasizes emerging issues beyond traditional medical ethic transparency, responsibility, justice, and autonomy must now be integrated throughout the lifecycle of AI-driven devices, including hearing aids [74]. Complementing this, a recent survey on user awareness and perceptions of auditory prostheses (hearing aids and cochlear implants) underscores the urgent need for enhanced education and awareness of privacy and security, as modern devices increasingly connect with digital networks and smart home ecosystems [75].

5.1. Conclusions and Recommendations for Future Research

Although a sharp rise in the rate of studies related to AI applications for the subject population was documented, such research is still relatively sparse and tends to be focused on only certain applications. Overall, this review indicates that the use of AI applications with DHH is a promising practice that professionals and researchers should carefully consider when working to help the population achieve their full potential. As the study [6] stated, only by continuing to research and in-vestigate these technologies will it be possible to fully exploit the new areas of application that have been discovered over the past two decades. Therefore, although there has been an increase in research on the ap-plications of AI for the DHH in recent years, this research still needs sig-nificant development in quality and scope, particularly in the Arab World. The results of this review provide interpretations that could positively influence the direction and methodological rigor of future research on DHH, including those with cochlear implants, as well as identify areas that should receive more rigorous and intensive investigation.

5.2. Limitations

One limitation of this review was the inclusion criterion requiring the term "artificial intelligence" or "AI" in the title of the article regarding the subject population, as some studies might have been missed because they described their particular application of artificial intelligence in different terms (e.g., machine learning, virtual reality). Furthermore, it is possible that some studies that examined sign language translation but that did not explicitly state one of the subject populations (DHH, HoH, or Deaf) in the title or the keywords might also have been missed by the search process. Thus, the results of the current study should be generalized with caution.

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