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Perspective

Digital Technology for Remote Hearing Assessment—Current Status and Future Directions for Consumers

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Abstract: Globally, more than 1.5 billion people have hearing loss. Unfortunately, most people with hearing loss reside in low- and middle-income countries (LMICs) where traditional face-to-face services rendered by trained health professionals are few and unequally dispersed. The COVID-19 pandemic has further hampered the effectiveness of traditional service delivery models to provide hearing care. Digital health technologies are strong enablers of hearing care and can support health delivery models that are more sustainable. The convergence of advancing technology and mobile connectivity is enabling new ways of providing decentralized hearing services. Recently, an abundance of digital applications that offer hearing tests directly to the public has become available. A growing body of evidence has shown the ability of several approaches to provide accurate, accessible, and remote hearing assessment to consumers. Further effort is needed to promote greater accuracy across a variety of test platforms, improve sensitivity to ear disease, and scale up hearing rehabilitation, especially in LMICs.

Keywords: audiology; hearing health; hearing loss; digital hearing evaluation; virtual hearing assessment

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1. Introduction

Hearing is key to everyday functioning, communication, and relationships in a hearing world. Unfortunately, more than 1.5 billion people globally have hearing loss; for nearly half a billion people, it is of a disabling degree [1]. The size of this global health burden and the lack of access to hearing health care require radical health care delivery changes, as highlighted in the recent World Report on Hearing [1]. The emergence of digital health technologies has been identified as an important trend to support scalable hearing health delivery models that are sustainable [2,3]. Digital health technologies have already demonstrated use as powerful enablers of hearing healthcare [4,5].

Unaddressed hearing loss has a significant impact on individuals and society and is a leading contributor to the global burden of disease [6]. Untreated or late-diagnosed hearing loss has clear links to social isolation [7], loneliness [8], cognitive decline [9], dementia, unemployment [10], and general health, including the rate of hospitalizations [11]. Hearing loss treatment, in most cases hearing aid provision, can significantly improve a person's function and participation to increase quality of life [12]. Despite the excellent treatments available, access to hearing health care is typically unavailable, especially in low- and middle-income countries (LMICs) where the number of patients per healthcare provider is exceedingly high, and resources are few [13,14]. For instance, in LMICs (e.g., sub-Saharan Africa, Argentina, and Mexico), there is typically fewer than one audiologist per million people [13,15]. Some types of hearing loss (e.g., noise-induced) can be prevented, but for other types (e.g., age-related hearing loss), early diagnosis and treatment are needed. In either case, regular hearing assessment plays a pivotal role in tracking hearing status and diagnosing hearing loss. The World Health Organization proposes early identification as one of the strategies to deal with the global burden of hearing loss [1]. Alternative ways to decentralize hearing assessment into rural areas could also reduce costs and improve widespread uptake. Digital technologies have increasingly demonstrated the potential to increase hearing health access via remote self- or community-health-worker-facilitated testing [5,16–18].

Digital options for self-testing have become even more relevant during the COVID-19 pandemic, which has restricted traditional services, given the need for social distancing. Traditional hearing evaluation setups are often in confined spaces such as soundproof booths, with long appointments and several tests involving equipment placement on and off the patient, all of which increase the risk of infection [19]. This is especially challenging in typical patients with hearing loss due to their advanced age and resultant mortality and morbidity risk [20]. It is thus no surprise that the use of technology to engage with the healthcare system has increased significantly amid the pandemic with a big move to telehealth. It is also unlikely that the utility of these technologies to provide healthcare will dissipate when the pandemic ends. While much research has been done on telehealth within the hearing healthcare space, the landscape for remote hearing assessment is quickly changing due to better access to mobile technology and internet connectivity. Globally, 3.8 billion people were mobile internet users by the end of 2019, an increase of 250 million since the end of 2018, of whom 90% of new users were from LMICs [21]. Therefore, remote care may aid in removing the ongoing access hurdles of formal audiological services and by providing context-appropriate solutions during the pandemic.

2. Remote Hearing Tests for Public Use

Traditional hearing healthcare services have proven ineffective to promote equitable access due to their resource-intensive and centralized nature, especially in LMICs. As a result, many digital applications have been developed to enable remote access. They can be classified as either clinical applications, used in medically regulated settings that are often decentralized, or consumer applications available directly to the public [22]. This review focuses on the status and potential directions of publicly available options that enable hearing assessment for consumers.

2.1. Pure-Tone Threshold Tests

A traditional hearing assessment includes gold-standard pure-tone audiometry in a formal, face-to-face appointment to diagnose hearing loss. This test describes the hearing sensitivity in each ear, obtained by assessing the lowest threshold intensity (decibel hearing level) across frequencies ranging from 250 to 8000 Hz. Many hearing evaluation applications are publicly available online or can be downloaded on smartphones via app stores like Google Playstore or Apple iStore, yet few are clinically validated against gold-standard measures [23,24]. Some applications use a form of traditional pure-tone audiometry to measure hearing thresholds across a specific frequency range [24]. However, as a sustainable solution, these tests pose a challenge due to varying test accuracy across devices [25]. This is because device calibration cannot be performed on all platforms, which is a component essential in quality control to ensure that the sound level presented to the user is consistent with the level intended for assessment (Table 1). Applications that apply a calibration function for more accurate results are usually downloadable smartphone apps from the iOS platform. This is possible because they are part of the Apple ecosystem available to users who own a set of standardized Apple hardware and software (Apple earbuds, iPhone with iOS operating system). An example is the uHear application, one of the most validated consumer applications in the peer-reviewed literature [23]. Peer and Fagan (2015) [26] used the uHear application on an iPhone 4 coupled to Apple earbuds and showed comparable results to formal audiometry at higher frequencies. In general, the accuracy of lower frequency thresholds, especially outside a soundproof booth, is lower due to the interference of ambient noise. A more recent study by Barczik and Serpanos (2018) replicated these results across the conventional frequency range using a newer iPhone 6 and Apple earbuds [25]. Two other studies found inaccurate results with the uHear application. The authors attributed the inaccuracies to the use of uncalibrated insert earphones [27,28]. These findings emphasize the need for calibrated devices when conducting pure-tone audiometry on consumer devices. With that in mind, Apple recently released a pure-tone audiometry module with calibration standards for their earphones as part of their research framework [22]. This development will likely support the availability of pure-tone tests directly to the public.

An advantage of this pure-tone approach is that it may also serve as the basis to augment hearing, as performed in traditional hearing aid fittings, using the same consumer electronics. One development along these lines is the "headphone accommodation" feature released for iOS 14 and Apple AirPods Pro in September 2020. This feature is reported to provide similar functions to a hearing aid by increasing the audibility of softer voices and tuning environmental sounds according to the user's needs [29]. While these advances in both hearing evaluation and amplification could provide a solution for people with milder forms of hearing loss, one major drawback is the high cost of Apple devices and app-incompatibility on other devices. Consequently, the availability and penetration of Apple smartphones are limited in LMICs [30].

2.2. Speech-Based Hearing Tests

Mobile applications that do not use tonal stimuli usually employ a speech-in-noise procedure to measure hearing at conversational loudness levels [24]. One measure commonly used is the digits-in-noise (DIN) test, which presents a series of three spoken digits (e.g., 3-5-8) in background masking noise [31]. The DIN varies the noise level relative to that of the digits up and down to find the ratio, termed the speech recognition threshold (SRT), where 50% of the digits are accurately recognized. The DIN SRT measure has strong reliability and validity and high sensitivity and specificity to detect hearing loss measured with pure-tone audiometry [31–35]. Moreover, unlike audiometry, the DIN is accurate across different devices and headphone types without the requirement of calibration (Table 1) [35]. This contributes to the DIN's sustainability as a digital hearing evaluation since it can be provided on several virtual platforms.

The first DIN test was developed and released as the Netherlands' national hearing test in 2004 for use over landline telephones [34]. DIN translations were developed in other countries and dialects, including the USA, France, Switzerland, United Kingdom, Australia, Poland, and Germany also for landline telephone [32,36,37]. More recently, the test was released on digital platforms, both online and as downloadable apps [35]. The first smartphone-based version, called *hearZA* [22], was released in South Africa in 2016. The World Health Organization released their *hearWHO* hearing screening app in 2019, and web app versions are also being used by consumer electronic companies such as Bose [38]. The switch to digital devices has the added benefit of more easily operated user interfaces and allows more high-fidelity broadband test signals instead of limited bandwidth signals offered by landline telephones [35]. Uptake of the DIN on digital devices has increased use dramatically [39]. With an estimated 81% of the global adult population being smartphone subscribers by 2025 [40], the digitization of self-tests like the DIN provides widespread access for more sustainable and scalable hearing care options.

Currently, DIN applications serve primarily as a hearing screening tool. Follow-up with a registered professional is recommended when a hearing loss is detected. Since the test is accurate across a range of consumer electronics, it is easy to implement as an additional, 24 h service for audiological websites to generate referrals [41]. Prospective patients who suspect a hearing loss can screen their hearing online and have the option to leave their information to be contacted by a hearing professional. Ratanjee et al. (2019) investigated the characteristics, behaviors, and readiness of persons seeking hearing healthcare online as part of a hybrid online and face-to-face care model. Interestingly, they showed that many people completed a digits-in-noise test online outside the typical 9:00 a.m. to 5:00 p.m. workday [42]. Therefore, the person seeking hearing care has the benefit of accessing services at times more convenient to them. Hybrid care models such as these could be sustainable across the patient journey as patients have indicated high satisfaction with this approach [43]. Another option is to provide these tests as freestanding applications on tablets or computers for people to use directly in facilities like pharmacies, clinics, and even retail stores.

Table 1. Summary of remote hearing assessment applications for consumers and their characteristics.

Stimulus Type	Pure-Tone Audiometry Applications	Digits-in-Noise Tests
Quantitative output	Hearing threshold estimation representative of the gold-standard audiogram	Speech recognition threshold or percentage-correct scores
Application	Screening on smartphone applications and website applications	Website applications Smartphone applications for direct consumer use. Freestanding applications in clinics
Advantages	Provides thresholds resembling the formal audiogram. Possibility to use thresholds to augment hearing loss using consumer electronics.	Quick to conduct. Less sensitive to ambient noise. Device and headphone calibration not required.
Limitations	Variable results across test devices and headphones. Require calibration to ensure accurate results. Sensitive to ambient noise in the test environment.	Results typically used for screening. Language dependent and requires translation and validation in other languages for widespread global uptake.
Examples of validated tests	uHear [25,26], Audiogram Mobile [44]	hearZA [33,35], hearWHO [33], USA computerized DIN [45]

3. Challenges

Remote hearing tests for the public and consumers are a practical way to increase access to services by capitalizing on the growth in personal digital technologies such as smartphones. However, detecting hearing loss is only the beginning of the hearing health care journey. Some consumer hearing evaluations can link potential patients to healthcare providers, but they do not resolve the problem of ill-equipped healthcare systems in LMICs or reduce infection risk (e.g., COVID-19) by minimizing face-to-face contact. Pure-tone audiometry remains the gold-standard measurement to provide hearing aid fitting. Traditionally, the way to obtain a hearing aid includes several visits to a professional who performs diagnostics of the auditory system and fits a hearing aid based on prescriptive gain and output targets. However, the Food and Drug Administration (FDA) published a nonbinding recommendation report in 2016 waiving the requirement for a medical evaluation before obtaining a hearing aid [46]. Furthermore, US President, Joe Biden, signed an executive order on 9 July 2021 that includes a directive to issue proposed rules within 120 days that will allow hearing aids to be sold over the counter [47]. As a result, the audiological landscape will rapidly change as newer categories of direct-to-consumer hearing aids (DTCs), which can be ordered online, and over-the-counter hearing aids (OTCs), which do not require a professional to fit, will become more accessible [48]. As technology advances, 'hearables', which are wearable smart-computing earbuds, may also become more widespread [49]. Remote assessment can serve all these new rehabilitation options and is an essential area for future application. While progress has been made toward accurate pure-tone audiometry through commercially available digital technology, there are persistent issues regarding test validity, accuracy, and access. Therefore, improving the accuracy of pure-tone tests would provide a way to self-program DTC and OTC hearing aids or even allow a smartphone to become an accessible, programmable intervention device, creating a more comprehensive and sustainable care pathway. An alternative is to look at ways other than pure tones to fit hearing aids. An example is the method used by Blamey and Saunders (2015), who use a simple online speech perception test to measure hearing and fit hearing aids. Their work show it is possible to use predicted audiometric thresholds derived from the speech perception test to accurately fit hearing aids [50].

Another challenge is how to serve people with more complex ear and hearing problems, such as differences in hearing loss between the left and right ear, or specific cases of ear disease (e.g., otitis media, wax impaction). In these circumstances, a medical assessment by an ENT doctor is recommended [51]. Currently, most consumer tests can only detect or indicate the severity of a hearing loss but cannot discriminate between types of hearing loss. A way to screen for potential ear disease will be of particular importance for people in LMICs, where the prevalence of ear diseases such as otitis media is higher than in high-income countries [52].

Whilst smartphone usage and mobile internet connectivity are increasing globally, they do not guarantee digital proficiency, which is characteristically higher for people who are younger, educated, employed, and live in more urban areas [53]. Furthermore, in LMICs, a lack of literacy and digital skills is the main barrier to the use of mobile technology and the internet [21]. Older adults, in particular, who make up the largest audiological cohort, may be hesitant about their ability to perform online hearing assessments with difficulty navigating complex screens, instructions, and user interfaces [54]. Irace et al. (2020) reviewed smartphone applications for hearing assessment in the elderly and found that many smartphone applications did not include simple interfaces and instructions to accommodate dexterity or mild cognitive impairment, hindering the use of touchscreens. In some instances, application instructions failed to indicate that the tests should be conducted using headphones [24]. Digital proficiency should, therefore, be a key factor considered when designing online applications to ensure usability for key demographics of people with hearing loss. Interestingly, however, in LMICs such as Kenya, smartphone penetration and usage amongst persons with hearing loss is similar to those without disabilities [55]. Digital devices already provide assistance to support persons with hearing loss to connect with others and access services including banking and payments [55].

A vital aspect to consider, and also a potential risk in the realm of digital healthcare, is data security. There are many applications available at no cost to the user, which could lead to uninformed test users falling trap to applications that sell data to third parties and risk their data privacy [24]. In addition, mobile health applications are targets of potential data theft. Vendors and providers should ensure that their applications meet the regulatory data security guidelines, and test users should carefully examine these applications before use [22].

4. Future Work

Online and app tests using pure-tone audiometry provide valuable output that approximates gold-standard audiometry in clinical practice. However, they are only accurate for a handful of devices when calibration functions can be applied and do not include bone conduction options available in clinics. On the other hand, speech-in-noise tests such as the DIN do not rely on calibration and are well-validated. However, they do not currently provide frequency-specific information that could be used to program hearing aids. One option to address the calibration issue of remote audiometry, and to facilitate diagnosis and program hearing aids using the DIN and other self-assessments, could be to ship calibrated self-test kits on digital devices directly to patients. Importantly, these advanced clinical self-test options could also allow the detection of possible ear disease. Our research has shown that when both pure-tone audiometry and DIN testing are completed together, conductive hearing loss may be distinguished from sensorineural hearing loss [56]. This is important, since conductive hearing loss is typically related to ear diseases like otitis media, whereas mild/moderate sensorineural hearing loss may be appropriately treated remotely using self-fit hearing aids.

Other, related efforts conducted directly on consumer electronics can be used to detect ear disease and discriminate between types of hearing loss. For example, developments in DIN testing [33] are combining different stimulus procedures (antiphasic, diotic, and monaural presentation) to discriminate conductive and unilateral sensorineural hearing loss from bilateral sensorineural hearing loss [33]. However, tests directed for public use should be as short and straightforward as possible to ensure maximum accuracy. Optimizing the test procedure for the shortest possible test duration while maintaining high test accuracy is important. A simple solution could be the provision of short case history questions that factor into the online test result and recommendation. Another, more advanced approach that can be embedded within a commercial self-test kit described above includes the use of a simple video-otoscope that uses machine learning to classify potential ear disease [57].

Previous work on speech-in-noise tests used noise-filtering techniques to increase sensitivity to hearing loss within a specific frequency range. Low-pass filtering stationary speech-shaped noise was first introduced by Leensen et al. [58]. The premise of the filtering technique is to assess speech recognition of a specific frequency range by masking the adjacent frequencies. In most forms of hearing loss, high frequencies are the first part of the hearing spectrum lost [59]. By attenuating the background masking noise in the higher frequencies, higher-frequency speech information is easier to recognize for people with normal hearing. However, people with high-frequency hearing loss do not have this advantage since they have reduced hearing ability within this frequency range [58]. This low-pass technique has increased the sensitivity and specificity of the digits-in-noise test to high-frequency hearing loss [60,61]. Future investigations into filtering methods to estimate hearing loss within low- and higher-frequency ranges could create new methods to prescribe and fit hearing aids without pure tone audiometry.

5. Conclusions

Digital health technologies are enabling remote hearing assessments to the public that are accessible, scalable, and sustainable. These test options are timely, given the significant discrepancy in need for hearing care and the ability of formal care models to ensure service delivery. The COVID-19 pandemic has further deterred people from accessing services due to the risk of infection. Digital hearing assessment, while not a solution in itself, is providing opportunities to decentralize initial hearing care access by capitalizing on increasing mobile internet connectivity. Future work needs to investigate methods to ensure greater test accuracy, sensitivity to ear disease, and ways to scale hearing rehabilitation using integrated digital solutions including hearing aids and other amplification options.

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References

1. World Health Organization [WHO]. World Report on Hearing. Available online: https://www.who.int/publications/i/item/world-report-on-hearing (accessed on 7 July 2021).
2. Swanepoel, D.W.; Clark, J.L.; Koekemoer, D.; Hall, J.W., III; Krumm, M.; Ferrari, D.V.; McPherson, B.; Olusanya, B.O.; Mars, M.; Russo, I. Telehealth in audiology: The need and potential to reach underserved communities. *Int. J. Audiol.* **2010**, *49*, 195–202. [CrossRef] [PubMed]
3. Swanepoel, D.; Clark, J.L. Hearing healthcare in remote or resource-constrained environments. *J. Laryngol. Otol.* **2019**, *133*, 11–17. [CrossRef]
4. Eksteen, S.; Launer, S.; Kuper, H.; Eikelboom, R.H.; Bastawrous, A.; Swanepoel, D.W. Hearing and vision screening for preschool children using mobile technology, South Africa. *Bull. World Health Organ.* **2019**, *97*, 672. [CrossRef]
5. Swanepoel, D.W. eHealth technologies enable more accessible hearing care. *Semin Hear* **2020**, *41*, 133–140. [CrossRef] [PubMed]
6. Vos, T.; Allen, C.; Arora, M.; Barber, R.M.; Bhutta, Z.A.; Brown, A.; Carter, A.; Casey, D.C.; Charlson, F.J.; Chen, A.Z. Global, regional, and national incidence, prevalence, and years lived with disability for 310 diseases and injuries, 1990–2015: A systematic analysis for the Global Burden of Disease Study 2015. *Lancet* **2016**, *388*, 1545–1602. [CrossRef]
7. Shukla, A.; Harper, M.; Pedersen, E.; Goman, A.; Suen, J.J.; Price, C.; Applebaum, J.; Hoyer, M.; Lin, F.R.; Reed, N.S. Hearing loss, loneliness, and social isolation: A systematic review. *Otolaryngol. –Head Neck Surg.* **2020**, *162*, 622–633. [CrossRef] [PubMed]
8. Sung, Y.-k.; Li, L.; Blake, C.; Betz, J.; Lin, F.R. Association of hearing loss and loneliness in older adults. *J. Aging Health* **2016**, *28*, 979–994. [CrossRef]
9. Lin, F.R.; Yaffe, K.; Xia, J.; Xue, Q.-L.; Harris, T.B.; Purchase-Helzner, E.; Satterfield, S.; Ayonayon, H.N.; Ferrucci, L.; Simonsick, E.M. Hearing loss and cognitive decline in older adults. *JAMA Intern. Med.* **2013**, *173*, 293–299. [CrossRef]
10. Jung, D.; Bhattacharyya, N. Association of hearing loss with decreased employment and income among adults in the United States. *Ann. Otol. Rhinol. Laryngol.* **2012**, *121*, 771–775. [CrossRef]
11. Hsu, A.K.; McKee, M.; Williams, S.; Roscigno, C.; Crandell, J.; Lewis, A.; Hazzard, W.; Jenerette, C. Associations among hearing loss, hospitalization, readmission and mortality in older adults: A systematic review. *Geriatr. Nurs.* **2019**, *40*, 367–379. [CrossRef]
12. Ferguson, M.; Maidment, D.; Henshaw, H.; Heffernan, E. Novel Approaches to Fostering Hearing Loss Self-Management in Adults: Evidence-Based Interventions for Adult Aural Rehabilitation: That Was Then, This Is Now. *Semin Hear* **2019**, *40*, 68–84.
13. Mulwafu, W.; Ensink, R.; Kuper, H.; Fagan, J. Survey of ENT services in sub-Saharan Africa: Little progress between 2009 and 2015. *Glob. Health Action* **2017**, *10*, 1289736. [CrossRef] [PubMed]
14. Wagner, R.; Fagan, J. Survey of otolaryngology services in Central America: Need for a comprehensive intervention. *Otolaryngol. –Head Neck Surg.* **2013**, *149*, 674–678. [CrossRef] [PubMed]
15. World Health Organization. Multi-Country Assessment of National Capactity to Provide Hearing Care. Available online: www.who.int/pbd/publications/WHOReportHearingCare_Englishweb.pdf (accessed on 15 June 2021).
16. Dawood, N.; Mahomed Asmail, F.; Louw, C.; Swanepoel, D.W. Mhealth hearing screening for children by non-specialist health workers in communities. *Int. J. Audiol.* **2020**, *60*, S23–S29. [CrossRef]
17. Van Wyk, T.; Mahomed-Asmail, F.; Swanepoel, D.W. Supporting hearing health in vulnerable populations through community care workers using mHealth technologies. *Int. J. Audiol.* **2019**, *58*, 790–797. [CrossRef]
18. De Sousa, K.C.; Swanepoel, D.W.; Moore, D.R.; Smits, C. A smartphone national hearing test: Performance and characteristics of users. *Am. J. Audiol.* **2018**, *27*, 448–454. [CrossRef]
19. Centers for Disease Control and Prevention. Interim U.S. Guidance for Risk Assessment and Public Health Management for Healthcare Personnel with Potential Exposure in a Healthcare Setting to Patients with Coronavirus Disease 2019 (COVID-19). Available online: https://www.cdc.gov/coronavirus/2019-ncov/hcp/guidance-risk-assesment-hcp.html (accessed on 15 April 2021).
20. Grasselli, G.; Zangrillo, A.; Zanella, A.; Antonelli, M.; Cabrini, L.; Castelli, A.; Cereda, D.; Coluccello, A.; Foti, G.; Fumagalli, R. Baseline characteristics and outcomes of 1591 patients infected with SARS-CoV-2 admitted to ICUs of the Lombardy Region, Italy. *JAMA* **2020**, *323*, 1574–1581. [CrossRef]
21. GSMA. The State of Mobile Internet Connectivity 2020. Available online: https://www.gsma.com/r/wp-content/uploads/2020/09/GSMA-State-of-Mobile-Internet-Connectivity-Report-2020.pdf (accessed on 18 June 2021).
22. Swanepoel, D.W.; De Sousa, K.C.; Smits, C.; Moore, D.R. Mobile applications to detect hearing impairment: Opportunities and challenges. *Bull. World Health Organ.* **2019**, *97*, 717. [CrossRef] [PubMed]
23. Bright, T.; Pallawela, D. Validated smartphone-based apps for ear and hearing assessments: A review. *JMIR Rehabil. Assist. Technol.* **2016**, *3*, e6074. [CrossRef]
24. Irace, A.L.; Sharma, R.K.; Reed, N.S.; Golub, J.S. Smartphone-Based Applications to Detect Hearing Loss: A Review of Current Technology. *J. Am. Geriatr. Soc.* **2021**, *69*, 307–316. [CrossRef]
25. Barczik, J.; Serpanos, Y.C. Accuracy of smartphone self-hearing test applications across frequencies and earphone styles in adults. *Am. J. Audiol.* **2018**, *27*, 570–580. [CrossRef] [PubMed]
26. Peer, S.; Fagan, J.J. Hearing loss in the developing world: Evaluating the iPhone mobile device as a screening tool. *S. Afr. Med. J.* **2015**, *105*, 35–39. [CrossRef]
27. Al-Abri, R.; Al-Balushi, M.; Kolethekkat, A.; Bhargava, D.; Al-Alwi, A.; Al-Bahlani, H.; Al-Garadi, M. The accuracy of IOS device-based uHear as a screening tool for hearing loss: A preliminary study from the Middle East. *Oman Med. J.* **2016**, *31*, 142.

28. Khoza-Shangase, K.; Kassner, L. Automated screening audiometry in the digital age: Exploring uHear(TM) and its use in a resource-stricken developing country. *Int. J. Technol. Assess. Health Care* **2013**, *29*, 42–47. [CrossRef]
29. Hearing Tracker. AirPods Pro Become Hearing Aids in iOS 14. Available online: https://www.hearingtracker.com/news/airpods-pro-become-hearing-aids-with-ios-14 (accessed on 7 July 2021).
30. Jamalova, M.; Constantinovits, M. The comparative study of the relationship between smartphone choice and socio-economic indicators. *Int. J. Mark. Stud.* **2019**, *11*, 11. [CrossRef]
31. Van den Borre, E.; Denys, S.; van Wieringen, A.; Wouters, J. The digit triplet test: A scoping review. *Int. J. Audiol.* **2021**, 1–18. [CrossRef]
32. Watson, C.S.; Kidd, G.R.; Miller, J.D.; Smits, C.; Humes, L.E. Telephone screening tests for functionally impaired hearing: Current use in seven countries and development of a US version. *J. Am. Acad. Audiol.* **2012**, *23*, 757–767. [CrossRef]
33. De Sousa, K.C.; De Wet Swanepoel, D.R.M.; Myburgh, H.C.; Smits, C. Improving sensitivity of the digits-in-noise test using antiphasic stimuli. *Ear Hear.* **2020**, *41*, 442. [CrossRef]
34. Smits, C.; Kapteyn, T.S.; Houtgast, T. Development and validation of an automatic speech-in-noise screening test by telephone. *Int. J. Audiol.* **2004**, *43*, 15–28. [CrossRef]
35. Potgieter, J.-M.; Swanepoel, D.W.; Myburgh, H.C.; Hopper, T.C.; Smits, C. Development and validation of a smartphone-based digits-in-noise hearing test in South African English. *Int. J. Audiol.* **2016**, *55*, 405–411. [CrossRef]
36. Jansen, S.; Luts, H.; Wagener, K.C.; Frachet, B.; Wouters, J. The French digit triplet test: A hearing screening tool for speech intelligibility in noise. *Int. J. Audiol.* **2010**, *49*, 378–387. [CrossRef]
37. Zokoll, M.A.; Wagener, K.C.; Brand, T.; Buschermöhle, M.; Kollmeier, B. Internationally comparable screening tests for listening in noise in several European languages: The German digit triplet test as an optimization prototype. *Int. J. Audiol.* **2012**, *51*, 697–707. [CrossRef]
38. Bose. Hearing Assessment. Available online: https://www.bose.com/en_us/landing_pages/hearing-screener.html (accessed on 8 July 2021).
39. STATISTA. Landline Phones Are a Dying Breed. Available online: https://www.statista.com/chart/2072/landline-phones-in-the-united-states/ (accessed on 18 June 2021).
40. GSMA. The Mobile Economy 2021. Available online: https://www.gsma.com/mobileeconomy/wp-content/uploads/2021/07/GSMA_MobileEconomy2021_3.pdf (accessed on 18 June 2021).
41. Ratanjee-Vanmali, H.; Swanepoel, D.W.; Laplante-Lévesque, A. Optimizing Audiology Websites to Increase Patient Reach. *Hear. J.* **2020**, *73*, 31–32. [CrossRef]
42. Ratanjee-Vanmali, H.; Swanepoel, D.W.; Laplante-Levesque, A. Characteristics, behaviours and readiness of persons seeking hearing healthcare online. *Int. J. Audiol.* **2019**, *58*, 107–115. [CrossRef] [PubMed]
43. Ratanjee-Vanmali, H.; Swanepoel, D.W.; Laplante-Lévesque, A. Patient uptake, experience, and satisfaction using web-based and face-to-face hearing health services: Process evaluation study. *J. Med. Internet Res.* **2020**, *22*, e15875. [CrossRef]
44. Corry, M.; Sanders, M.; Searchfield, G.D. The accuracy and reliability of an app-based audiometer using consumer headphones: Pure tone audiometry in a normal hearing group. *Int. J. Audiol.* **2017**, *56*, 706–710. [CrossRef]
45. Folmer, R.L.; Vachhani, J.; McMillan, G.P.; Watson, C.; Kidd, G.R.; Feeney, M.P. Validation of a computer-administered version of the digits-in-noise test for hearing screening in the United States. *J. Am. Acad. Audiol.* **2017**, *28*, 161–169. [CrossRef] [PubMed]
46. US Food and Drug Administration. Immediately in Effect Guidance Document: Conditions for Sale for Air-Conduction Hearing Aids Guidance for Industry and FOOD and Drug Administration Staff. Available online: http://www.fda.gov/downloads/MedicalDevices/DeviceRegulationandGuidance/GuidanceDocuments/UCM531995.pdf (accessed on 18 June 2021).
47. MEDTECHDIVE. Biden Order Takes Aim at High Cost of Hearing Aids, Calls for OTC Sales. Available online: https://www.medtechdive.com/news/biden-order-takes-aim-at-high-cost-of-hearing-aids-calls-for-otc-sales/603114/ (accessed on 9 July 2021).
48. Tracker, H. OTC Hearing Aids Regulations to Be Published by 2022. Available online: https://www.hearingtracker.com/news/otc-hearing-aids-regulations-to-be-published-by-2022 (accessed on 8 July 2021).
49. Plazak, J.; Kersten-Oertel, M. A Survey on the Affordances of "Hearables". *Inventions* **2018**, *3*, 48. [CrossRef]
50. Blamey, P.J.; Blamey, J.K.; Saunders, E. Effectiveness of a teleaudiology approach to hearing aid fitting. *J. Telemed. Telecare* **2015**, *21*, 474–478. [CrossRef]
51. AAO-HNS. Position Statement: Red Flags-Warning of Ear Disease. Available online: https://www.entnet.org/content/position-statement-red-flags-warning-ear-disease (accessed on 8 July 2021).
52. Graydon, K.; Waterworth, C.; Miller, H.; Gunasekera, H. Global burden of hearing impairment and ear disease. *J. Laryngol. Otol.* **2019**, *133*, 18–25. [CrossRef]
53. Pew Research Center. Mobile Fact Sheet. Available online: https://www.pewresearch.org/internet/fact-sheet/mobile/ (accessed on 30 June 2021).
54. Sarkar, U.; Gourley, G.I.; Lyles, C.R.; Tieu, L.; Clarity, C.; Newmark, L.; Singh, K.; Bates, D.W. Usability of commercially available mobile applications for diverse patients. *J. Gen. Intern. Med.* **2016**, *31*, 1417–1426. [CrossRef]
55. GSMA. Understanding the Mobile Disability Gap. Available online: https://www.gsma.com/mobilefordevelopment/resources/understanding-the-mobile-disability-gap/ (accessed on 8 July 2021).

56. De Sousa, K.C.; Smits, C.; Moore, D.R.; Myburgh, H.C.; Swanepoel, D.W. Pure-tone audiometry without bone-conduction thresholds: Using the digits-in-noise test to detect conductive hearing loss. *Int. J. Audiol.* **2020**, *59*, 801–808. [CrossRef]
57. ENT & Audiology News. Digital Otoscopy Wiht AI Diagnostic Support: Making Diagnosis of Ear Disease More Accessible. Available online: https://www.entandaudiologynews.com/development/spotlight-on-innovation/post/digital-otoscopy-with-ai-diagnostic-support-making-diagnosis-of-ear-disease-more-accessible (accessed on 8 July 2021).
58. Leensen, M.C.; de Laat, J.A.; Snik, A.F.; Dreschler, W.A. Speech-in-noise screening tests by internet, part 2: Improving test sensitivity for noise-induced hearing loss. *Int. J. Audiol.* **2011**, *50*, 835–848. [CrossRef]
59. Dubno, J.R.; Eckert, M.A.; Lee, F.-S.; Matthews, L.J.; Schmiedt, R.A. Classifying human audiometric phenotypes of age-related hearing loss from animal models. *J. Assoc. Res. Otolaryngol.* **2013**, *14*, 687–701. [CrossRef] [PubMed]
60. Motlagh Zadeh, L.; Silbert, N.H.; Swanepoel, D.W.; Moore, D.R. Improved Sensitivity of Digits-in-Noise Test to High-Frequency Hearing Loss. *Ear Hear.* **2021**, *42*, 565–573. [CrossRef] [PubMed]
61. Vlaming, M.S.; MacKinnon, R.C.; Jansen, M.; Moore, D.R. Automated screening for high-frequency hearing loss. *Ear Hear.* **2014**, *35*, 667. [CrossRef] [PubMed]