**Validity of hearing screening using hearTest smartphone-based audiometry: performance evaluation of different response modes**

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**Abstract**

**Objective:** To investigate the validity of hearing screening with hearTest smartphone-based audiometry and to specify test duration addressing the two response modes and hearing loss criteria.  **Design:** A diagnostic accuracy study comparing hearing screening with conventional audiometry. **Study sample:** 340 individuals, aged between 5 and 92 years. **Results**: Of the 340 participants, 301 undertook all test procedures (273 adults and 28 children). Sensitivity and specificity were >90% for hearTest hearing screening to identify disabling hearing loss for both response modes with adults and children. We found similar sensitivity in identifying any level of hearing loss for both response modes in children, with specificity >80%, and for the self-test mode in adults. Low specificity was observed when identifying any level of hearing loss in adults using the test-operator mode. In adults, there was a signiﬁcant difference between test duration for the test-operator and self-test modes. **Conclusion**: Hearing screening using hearTest smartphone-based audiometry is accurate for the identification of both disabling hearing loss and any level of hearing loss in adults and children in the self-test response mode. The test-operator mode is also an option for children; however, it does not provide good accuracy in identifying mild level of hearing loss in adults.

**Keywords:** Hearing loss; mass screening; mobile applications; sensitivity and specificity.

**Introduction**

The World Health Organization (WHO) estimates that 360 million people, approximately 5% of the global population, experience disabling hearing loss. Adults are more affected than children, representing 91% of all cases1. It is estimated that 80% of people with hearing loss live in low- and middle-income countries (LMICs), where, currently, there are few screening programmes for the identification of hearing loss2,3. If hearing loss is not diagnosed in children or adults, it may negatively impact on communication, social interaction, learning and cognition. This, in turn, can have adverse effects on educational attainment, quality of life and inclusion in the labour market, leading to high social and economic costs4-7.

Conventional audiometry is considered the gold standard test for hearing loss detection8. Screening programmes require high cost equipment, sound-treated environment (i.e. sound booths) and specialist professionals. In LMICs, there is a dearth of human and technical resources available for the identification of hearing loss, which presents substantial barriers9.

Innovative technologies have been developed to try and improve the feasibility of hearing screening and identification of hearing loss. These include apps for smartphones and tablets that enable non-hearing trained workers to screen hearing, driven by the global smartphone penetration, as well as the application of new technologies for health (mhealth). A systematic review conducted in 2015 identified 26 available apps for ear and hearing assessments but found that only four of them had been validated in peer-reviewed literature9.

Studies conducted in North America10-18, South Africa8,19-26, Asia27-32, Europe33-35 and South America36 in soundproof booths or quiet rooms, suggested good accuracy of these hearing screening smartphone apps, compared to conventional audiometry or other hearing screening procedures, although several were conducted by non-independent researchers (e.g. app developers)11,12,20,21,23,24,26,36.

The majority of research on the accuracy of hearing screening apps focusses on a self-test mode to estimate hearing thresholds, in which the subjects themselves register their response in the smartphone or tablet8,10-19,24,25,27-32,34,35. A test-operator mode is also available in some apps20,23,33 in which the participant signals when they hear a sound by raising their hand or arm and the examiner records the response in the app. This may be beneficial for many children, and for adults who are not familiar with touchscreen technology or who have limited manual dexterity. However, data is lacking on the feasibility and accuracy of these two different modes compared to conventional audiometry.

Self-test mode was selected in the only two studies that investigated the accuracy of hearTest smartphone-based audiometry in identifying hearing loss23,25 compared to conventional audiometry. The test mode of one of these studies was later changed to test-operator, due to participant difficulties in handling the touchscreen23. In these studies, the mean test duration using the self-test mode in soundproof booth for adults was lower than the mean test duration for adolescents25 and a statistically significant difference was observed between test duration in the soundproof booth and silent room among adults using the operator-test mode23. However, neither presented diagnostic accuracy measurements for the test, nor did they include participants under 15 years in their study population.

Considering the diversity of the population that may benefit from hearing screening, assessing the accuracy of these response modes in hearing screening smartphone apps is essential in informing recommendations about their use in hearing health programmes. Furthermore, it is necessary to explore this in independent studies. The aim of this study, therefore, is to investigate the validity of hearing screening with hearTest smartphone-based audiometry and to specify test duration addressing the two response modes (self-test and test-operator) and hearing loss criteria, compared to conventional audiometry.

**Materials and methods**

***Design***

A diagnostic accuracy study comparing smartphone-based audiometry (hearTest) to conventional audiometry, the gold standard.

***Participants***

 Participants were recruited from the Speech, Language and Hearing (SLH) Teaching Centre at the Federal University of Bahia (Universidade Federal da Bahia: UFBA), in the Northeast of Brazil, between November 2017 and May 2018. Individuals aged four years and older who did not present with an obstruction (e.g. wax or foreign body) during a visual inspection of the ear canal were eligible for inclusion in the study. Exclusion criteria included inability to understand the hearing screening procedure, dropout during the tests and inconsistent responses to conventional audiometry.

 The sample size was calculated according to Flahault et al (2005)37, assuming a sensitivity of 75% and a lower 95% confidence limit not falling below 0.50 with 0.95 probability, resulting in a required sample size of 310 individuals. Incorporating a 10% margin to cover potential refusals, the final study sample was 341 individuals.

 ***Equipment***

 We used automated hearTest smartphone-based audiometry to investigate the validity of hearing screening at frequencies of 0.5, 1, 2, 3, 4, 6, and 8 kHz. This system, developed by the hearX Group, was loaded onto a Samsung Galaxy A3 Android smartphone connected to calibrated Sennheiser HD280 circum-aural headphones. The hearTest enables the estimation of air-conduction hearing thresholds at frequencies of 0.5 to 8 kHz and intensities between 10 and 90 dB HL. For 8 kHz frequency, the maximum test tone intensity is 80 dB HL. and. Trained students from the SLH Course conducted the hearing screening in a quiet room without acoustic treatment using the different response modes available on the system: self-test and test-operator mode.

 hearTest was compared to conventional audiometry, which was considered the gold standard. Conventional audiometry included the measurement of air-conduction and bone-conduction hearing thresholds and were conducted in a soundproof booth using a clinical audiometer with TDH‐39 earphones.

***Procedures***

 All participants responded to a brief interview to obtain socio-demographic and hearing history, and to investigate smartphone use prior to study participation, through the following question “Have you ever used a touch-sensitive device like this (phone, tablet, etc.)?”

The hearing screening was conducted using the two different response modes (self-test and test-operator), with the first mode alternating according to the order in which participants started screening. In the self-test mode, we tested the thresholds at frequencies of 0.5, 1, 2, 3, 4, 6 and 8 kHz; the participant was advised to press the button on the smartphone screen whenever they heard a sound. If a patient did not respond to the first 40 dB HL, the intensity was increased by 20 dB HL until a response occurred. However, if a patient responded appropriately to the initial testing sequences, subsequent frequency tests began at 30 dB HL. The random waiting interval was 750ms - 4000ms, with tone presentation at 1200ms and a silent interval of 1200ms. In case of a false response rate above 20%, the test was automatically interrupted and restarted, to a maximum of three attempts.

 In the test-operator response mode, the test sequence was also automated, and the participant was instructed to signal by raising their hand or arm when they heard the sound, similar to the conventional audiometry response. Trained examiners from the SLH Course, positioned behind the participant, provided test stimulus, varying the period of silence between each presentation (manual) and recording a positive or negative response. Hearing screening was always initiated in the left ear at 40 dB HL at a frequency of 1 kHz, in line with app specifications. We then obtained thresholds at frequencies of 2, 3, 4, 6, 8 kHz and 0.5 Hz and retested the threshold obtained at 1 kHz. When the participant heard the test tone, the intensity was reduced by 10 dB HL and then reapplied. If the sound was not identified, the intensity was increased by 5 dB HL until the participant recorded a positive response (Hughson Westlake technique)38. Where there was a difference in response of 40 dB HL or more, compared to the contralateral ear, participants were retested with automatic sound masking.

Prior to hearing screening with the hearTest, the students conducted test training, using the app’s conditioning functionality at a frequency of 1 kHz in both ears to help the participant identify and respond to sounds. A test tone of 40 dB HL was initially applied, reduced by 10 dB until the sound could no longer be identified. If the participant could not identify the initial 40 dB sound, this was increased by 10 dB HL increments until it was heard. Each participant went through a test training before the hearing screening, according to which response mode they would use in the screening.

 The time required to perform hearing screening in each mode was recorded by the app. For both response modes, we considered auditory threshold per frequency to be the lowest intensity at which the patient provided two positive responses. Environmental sound monitoring was undertaken before each test. Hearing screening was only conducted when, according to the app, the level of environmental sound did not exceed the maximum permissible ambient noise levels for audiometric testing with HD 280 headphone (range 27 to 44 dB SPL according to the frequency). During the test the monitoring noise function enables real-time background noise analysis in relation to the test frequencies without however automatically rejects a response when the environmental sound level is high.

Following hearing screening with hearTest, we carried out conventional audiometry for each participant. We obtained the hearing thresholds for air-conduction using an intensity stimulus ranging from -10 to 120 dB HL (0.5, 1, 2, 3, 4, 6, and 8 kHz) and bone-conduction (0.5, 1, 2, 3 and, 4 kHz). All the audiological assessment procedures were conducted by an SLH professional from the service or students from the final year of the SLH Course supervised by a skilled professional not linked to the study and masked to the hearing screening test.

***Data analysis***

 Data was double entered, by two different researchers, using the EpiData programme developed for Windows and analyses were performed using Stata 14.2. The variable for monthly per capita household income was stratified in line with the World Bank definition used to classify people living in poverty in developing countries39.

For both test duration and accuracy analyses, we only considered participant ears which underwent all three test procedures (hearing screening using hearTest in self-test mode, in test-operator mode and conventional audiometry), as well as the hearing thresholds obtained at frequencies of 0.5, 1, 2 and 4 kHz, since these frequencies are commonly used to determine the pure tone average which, in turn, establishes presence or absence of hearing loss, according to WHO definitions1.

 The distribution of time required to perform hearing screening was not normally distributed (Shapiro-Wilk test of normality), and thus non-parametric analysis was conducted (Wilcoxon signed rank test) to determine if there were significant differences between time required to perform hearing screening by different response mode (self-test and test-operator) to both groups, adults and children.

 The hearing thresholds obtained for each ear in the hearTest smartphone app screening and conventional audiometry were classified as pass/fail according to response mode using two definitions of hearing loss: a) disabling hearing loss, “failure” in the hearing screening occurred when the pure tone average (PTA) of thresholds at 0.5, 1, 2, and 4 kHz were above 40 dB HL for adults (≥15 years old) and above 30 dB HL for children (between 4 and 14 years old), in line with WHO classifications1; and b) any level of hearing loss, “failure" in the hearing screening occurred when the average thresholds between 0.5 and 4 kHz were above 25 dB HL, independent of participant age. Proportions of failure in hearing screening by response mode (self-test and test-operator) were compared using the McNemar χ 2 test and exact binomial test.

 The sensitivity (Se) and specificity (Sp) measures for adults and children and the predictive positive (PPV) and negative values (NPV) for the two response modes resulting from the hearTest screening, compared to the conventional audiometry result, were classified according to the same pass/fail criteria. The PTA of thresholds at 0.5, 1, 2, and 4 kHz measured in conventional audiometry was considered gold standard and classified using the same definitions. In order to summarize accuracy into a single numeric value, the Youden index (J) was calculated as: J= Se + Sp – 1. When Se and Sp are perfect, J equals 1, whereas 0 indicates that agreement is purely due to chance40. Based on previous studies9,26, a Se and Sp of 80% and a Youden Index of 70% or above were established as the cut-off points for good accuracy.

***Ethical considerations***

This study was approved by the Institute of Health Sciences’ Research Ethics Committee, under opinion number 1.567.407. All participants signed informed consent forms.

**Results**

Of the 378 participants invited, 24 declined, and 14 individuals were excluded because they did not understand the test procedures (n=9) or they withdrew (n=3), or because of inconsistent responses to the hearing assessment (n=2). The final study population was composed of 300 adults, ranging from 15 to 92 years old (mean=53 years) and 40 children aged between 5 and 14 years (mean=9 years). Table 1 summarizes the characteristics of participants. The majority of participants for both groups were female and had used smartphones prior to study participation. More adults reported previous audiological assessment (60%) than children (27%).

 Of the 340 individuals included in the study, 301 undertook hearTest hearing screening in the two response modes: self-test and test-operator, 28 children (56 ears) and 273 adults (546 ears). False negative responses in self-test mode led to invalid hearTest results (n=35). Just over one third (34%) of these false negative responses were children (n=12), with a mean age of 8 years (ranging from 5 to 10 years). The majority of these children had a history of mobile touchscreen use prior to the study (n=10) and had not undertaken hearing assessment before the study (n=8). The majority of the 23 adults with a mean age of 55 years (range 23 to 91 years), who exhibited false negatives, reported hearing assessments prior to the study (n=15) and did not have experience with touchscreen mobile devices (n=14). Four individuals did not complete the test-operator mode (three adults reported fatigue, and one adult presented inconsistent responses).

 Table 2 presents the proportion of failure rates in conventional audiometry and hearTest screening. Overall, the proportion of hearing screening failures among adults and children was higher for both hearing loss classification criteria using the hearTest, independent of response mode or assessed ear, compared to conventional audiometry.

 Among the adults, the proportion of hearing screening failures was significantly greater in test-operator mode than in self-test mode for the right ear and for both ears (ps< 0.05). This finding held for both disabling hearing loss and any level of hearing loss (ps< 0.05). In contrast, there was no statistically significant difference between the proportion of failures for the left ear in both response modes and for both hearing loss criteria. For children, no significant difference was observed between the proportion of failures in hearing screening when we considered the different response modes.

Table 3 presents hearing screening accuracy according to response mode for the left and right ears and both ears together in order to identify hearing loss in adults. We found sensitivity >95% and specificity >90% for the identification of disabling hearing loss. Similar sensitivity findings were observed for the criterion any level of hearing loss, although the specificity in test-operator mode was just below the cut-off for good accuracy (≥ 80%). High PPVs and NPVs were observed in both response modes and hearing loss criteria. Youden Index results per ear and for both ears were ≥70% for hearing screening using hearTest smartphone-based audiometry to identify the different hearing loss criteria using both response modes, with the highest values for disabling hearing loss and self-test mode, compared to any level of hearing loss and test-operator mode.

For children, we observed 100% sensitivity for hearing screening using hearTest smartphone-based audiometry to identify disabling hearing loss and any level of hearing loss in both response modes (Table 4). Specificity was >90% for identifying disabling hearing loss and >80% for any level of hearing loss, with the highest values observed in self-test mode for both hearing loss criteria. Overall, low PPVs were identified, with those for any level of hearing loss and test-operator mode criteria lower than those observed for disabling hearing loss and self-test mode. Given the Youden Index, the accuracy of hearing screening was classified as good for both response modes and hearing loss criteria.

In terms of the test duration of hearing screening in adults, the self-test mode ranged from 3 to 15 minutes, with a median longer (8 minutes) than the previous study (interquartile range - IQR=6-10). The test-operator mode took between 2 and 14 minutes, with a median of 6 minutes (IQR=5-7). Test-operator mode was significantly faster than self-test mode (p<0.0001) in adults. For children, the self-test mode ranged from 3 to 11 minutes, with a median of 5 minutes (IQR=4-6). The test-operator mode took between 3 and 14 minutes, with a median of 4.5 minutes (IQR=4-6). There was no statistically significant difference between the duration of hearing screening using the different response modes for the children.

**Discussion**

 Our results indicate good accuracy for hearing screening using hearTest smartphone-based audiometry in both self-test and test-operator response mode to identify disabling hearing loss in adults and children compared to conventional audiometry, the gold standard. When we examined the criterion for any level of hearing loss, we found good test accuracy for both response modes in children but only for the self-test mode in adults.

Good accuracy in hearing screening using hearTest smartphone-based audiometry was demonstrated through high sensitivity, specificity and Youden Index. Overall, the self-test mode provided slightly greater accuracy than the test-operator mode. This is somewhat surprising, given that the test-operator mode is similar to the conventional tonal audiometry response procedure, which most adult participants had reportedly undergone in the past. One reason for this finding could be that greater attention may be paid when the individual is responsible for recording their own test response. In addition, most participants, both adults and children, reported previous experience with touchscreen technology, which may also contribute to the findings. Although test-operator mode had slightly lower Youden index values, it has the benefit of facilitating the inclusion of individuals with limited touchscreen experience or poor manual dexterity. This is also valid for the adult participants who were not successfully evaluated through the self-test mode, the majority (65%) of whom reported no prior experience with mobile touchscreen devices.

The greater proportion of hearing screening failures in adults using hearTest smartphone-based audiometry in test-operator mode, as opposed to self-test mode, for both hearing loss criteria corroborates the hypothesis that individuals pay greater attention when recording their own response to the test (self-test mode). We observed that this statistically significant difference between adults was restricted to the right ear and both ears. This finding may be due to the fact that hearTest smartphone-based audiometry hearing threshold measurements are always initiated in the left ear. This hearTest feature may contribute to learning about test response for the second ear (the right one), but it may also lead to tiredness, which interferes in the level of attention paid in the second ear assessment. However, no difference was observed in children in the proportion of failures according to response mode for the two hearing loss criteria. The small number of child participants may have restricted the power of this analysis.

 There are limited available studies with which to compare our results due to variation in test methodologies and tester modes. However, we identified four studies using hearScreen, a screening version of hearTest, which provides a pass/fail result at frequencies of 1, 2, and 4 kHz (rather than seeking thresholds), with a different screening cut-off for adults and children. Of these, two studies20,21 used audiometric screening as their gold standard and another24 only presented the test and re-test results for the app itself. A study by Louw et al (2017)26 adopted the same gold standard as ours (conventional audiometry) but defined the pass/fail criteria as 35 dB HL for adults and 25 dB HL for children (< 16 years old). Sensitivity was measured as 81.7% (95%CI 74.3, 87.4) and specificity as 83.1% (95% CI 74.1, 89.6) with testing occurring in a quiet room, using test-operator response mode. If we compare these results with our test-operator ones, we identified higher sensitivity levels for the two hearing loss criteria (>95%) for adults and children, but a lower specificity for any level hearing loss (PTA >25 dB) only among adults (<80%). The differences between the Louw et al26 findings and ours may be attributed to the tested frequencies (1, 2 and 4 kHz), the criterion adopted to define hearing loss and the use of a single accuracy measure for adults and children.

Previous studies to investigate the validity of hearTest smartphone-based audiometry do not present diagnostic accuracy measures, limiting comparison with our findings for these measures23,25. The first investigation into the hearTest smartphone-based audiometry prototype was conducted in 2016, in South Africa23 with adults aged between 18 and 88. That particular study estimated hearing thresholds in both a soundproof and a non-acoustically treated environment, using the test-operator response mode. Test duration in the non-acoustically treated environment was 5.9 minutes, similar to that observed in adults in our study (6 minutes). In 2017, a South African validation study comparing hearTest smartphone-based audiometry with conventional audiometry25 was conducted with adults (24 to 92 years old) and adolescents (16 to 21 years old) using the self-test mode in soundproof booths. The mean test duration for the hearTest was 6.7 minutes (SD=1.5) for adults and 7.1 minutes (SD=1.2) for adolescents. In our study, the mean test durations between participants of similar ages (>14 years) was 8 minutes. Distinct test environments may also contribute to these differences, given the influence of background noise on thresholds.

 In our study, we identified a difference between the test duration of hearing screening using hearTest smartphone-based audiometry (0.5 to 8 kHz) in adults according to response mode, with the test-operator mode two minutes faster than the self-test one. We did not observe any response mode influence on test duration for children. Previous studies using hearTest smartphone-based audiometry to measure hearing thresholds only utilized one of the available test response modes23,25, which does not allow for comparison with our findings.

 One of the alternatives for estimating hearing loss in large populations has been the self-reported hearing loss tools41. However, these have only addressed the adult population (>15 years) and in most of these studies sensitivity and specificity levels were lower than those identified in our study42-46. In light of this, hearTest smartphone-based audiometry emerges as an alternative to self-report hearing loss with better accuracy in identifying hearing loss and with the advantage of enabling testing children.

 Despite planning for the inclusion of children over four years old, only children aged five years or above were able to undertake the three test procedures in our study. During data collection, we observed that children under five years old had false positive responses, and consequently the test was automatically interrupted. We also noticed that these children became easily fatigued, and their tests demonstrated a higher frequency of false positive responses when they performed the second hearing screening, resulting in a decline in participation during the test. These findings suggest that children under five years old may not be good candidates for hearing screening using hearTest smartphone-based audiometry, given the usual test procedures. However, the use of play strategies, such as conditioned audiometry for children, in hearing screening for children under five could be adopted to increase the target population’s age range.

There were some study limitations. Results for children should be interpreted cautiously due to small number of subjects. Hearing screening using hearTest smartphone-based audiometry was conducted in a non-acoustically treated environment with different headphones from those used to measure hearing thresholds using conventional audiometry (TDH39), which may have influenced the hearing thresholds obtained and consequently the decrease in accuracy measures. Despite this, high sensitivity and specificity were found for hearing screening with hearTest smartphone-based audiometry in a non-acoustically treated environment compared to conventional audiometry in soundproof booths. Measuring hearing thresholds in a quiet room (rather than a sound-proof booth) was a methodological choice, in order to approximate the test environments of locations routinely used in population studies, such as primary healthcare rooms or the residence of individuals being screened. In addition, we note that our hearTest smartphone-based audiometry hearing screening was undertaken using calibrated circum-aural headphones and followed measurements from the app itself to indicate the acceptable noise level for hearing threshold research.

Our study also has strengths. It is the first validation study to include both children and adults. It was conducted by independent researchers (i.e. not affiliated with app developers) and the findings support the recommendation for hearTest smartphone-based audiometry as an easy-to-use and low cost tool for hearing screening, enabling the investigation of hearing loss in a range of populations, and promoting identification in situations where access to conventional audiometry is not feasible. Furthermore, it could also be used to investigate the prevalence of hearing loss in population studies. It is worth noting that both screening response modes may be utilized, with test-operator mode potentially facilitating the participation of individuals with little experience of touchscreen technology and limited manual dexterity. Similarly, the self-test mode could expand the provision of hearing screening programmes in locations where there is a lack of suitable human resources.

**Conclusion**

 In summary, we have shown that hearing screening using hearTest smartphone-based audiometry is accurate for identification of both disabling hearing loss and any level of hearing loss in self-test response mode for adults and children aged five years and older. The test-operator mode is also an option for children; however, among adults it does not provide good accuracy in identifying mild level of hearing loss. This suggests that it is a feasible screening alternative when conventional audiometry is not available.

This work was supported by the [National Council of Technological and Scientific Development (Conselho Nacional de Desenvolvimento Científico e Tecnológico: CNPq #1] under Grant [number429093/2016-0] and [Vice-president for Research, Creation and Innovation (Pró-Reitoria de Pesquisa, Criação e Inovação) of the Federal University of Bahia (Universidade Federal da Bahia: UFBA, Programa de apoio a Jovens Professores Doutores – Propesq) #2] under Grant [004/2016].

Conflicts of Interest: The authors declare no conflict of interest.

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Table 1. Study population characteristics (N=340)

|  |  |
| --- | --- |
| Characteristics |  |
|  |  | N | % |
| **Adults (≥ 15 years) = 300** |  |
|  |  |  |  |
|  | Sex | Male | 100 | 33.3 |
|  |  | Female | 200 | 66.7 |
|  |  |  |  |  |
|  | Age | 15 - 25 | 20 | 6.7 |
|  |  | 26 - 40 | 54 | 18.0 |
|  |  | 41 - 60 | 123 | 14.0 |
|  |  | 61 - 80 | 90 | 30.0 |
|  |  | ≥ 81 | 13 | 4.3 |
|  |  |  |  |  |
|  | School | Never | 12 | 4.0 |
|  |  | Primary  | 71 | 23.7 |
|  |  | Secondary | 174 | 58.0 |
|  |  | College or more | 43 | 14.3 |
|  |  |  |  |  |
|  | Monthly per capita household income  | ≤ 406.00 | 92 | 30.7 |
|  |  | > 406.00 | 180 | 60.0 |
|  |  | Not Available  | 28 | 9.3 |
|  | Employed  | No  | 177 | 59.0 |
|  |  | YesNot Applicablea | 1176 | 39.02.0 |
|  |  |  |  |  |
|  | Previous hearing assessment | No  | 118 | 39.3 |
|  |  | Yes | 182 | 60.7 |
|  |  |  |  |  |
|  | Touchscreen mobile use previous to study | No | 105 | 35.0 |
|  | Yes | 195 | 65.0 |
|  |  |  |  |
|  |  |  |  |
| **Children (≤ 14 years) = 40** |  |  |  |
|  | Sex | Male | 18 | 45.0 |
|  |  | Female | 22 | 55.0 |
|  |  |  |  |  |
|  | Age | ≤ 7 | 11 | 27.5 |
|  |  | 8 - 10 | 20 | 50.0 |
|  |  | 11 -14 | 9 | 22.5 |
|  |  |  |  |  |
|  | School | Primary | 32 | 80.0 |
|  |  | Secondary | 8 | 20.0 |
|  |  |  |  |  |
|  | Monthly per capita household income  | ≤ 406.00 | 26 | 65.0 |
|  |  | > 406.00Not Available | 95 | 22.512.5 |
|  |  |  |  |  |
|  | Previous hearing assessment | No  | 29 | 72.5 |
|  |  | Yes | 11 | 27.5 |
|  |  |  |  |  |
|  | Touchscreen mobile use previous to study | No  | 4 | 10.0 |
|  |  | Yes | 36 | 90.0 |

a underaged participants (≤17 years old)

Table 2. Failure rate in conventional audiometry and hearTest screening

|  |  |  |  |
| --- | --- | --- | --- |
|  | Disabling Hearing Loss |  | Any level of Hearing Loss |
| Procedures/ Hearing Loss definition | Left | Right | All |  | Left | Right | All |
|  | % (N) | % (N) | % (N) |  | % (N) | % (N) | % (N) |
| Adults (273 individuals/546 ears) |  |  |  |  |  |  |  |
|  | Pure tone audiometry | 28.6 (78) | 30.0 (82) | 29.3 (160) |  | 42.9 (117) | 43.6 (119) | 43.2 (236) |
|  |  |  |  |  |  |  |  |  |
|  | Self-test  | 32.2 (88) | 34.1 (93) | 33.1 (181) |  | 53.8 (147) | 54.6 (149) | 54.2 (296) |
|  |  |  |  |  |  |  |  |  |
|  | Test-operator | 34.1 (93) | 36.3 (99) | 35.2 (192) |  | 56.4 (154) | 57.5 (157) | 57.0 (311) |
|  |  |  |  |  |  |  |  |
| Children (28 individuals/56 ears) |  |  |  |  |  |  |  |
| Pure tone audiometry | 10.7 (3) | 7.1 (2) | 8.9 (5) |  | 10.7 (3) | 7.1 (2) | 8.9 (5) |
|  |  |  |  |  |  |  |  |
| Self-test  | 10.7 (3) | 10.7 (3) | 10.7 (6) |  | 21.4 (6) | 14.3 (4) | 17.9 (10) |
|  |  |  |  |  |  |  |  |
| Test-operator  | 17.9 (5) | 10.7 (3) | 14.3 (8) |  | 21.4 (6) | 25.0 (7) | 23.2 (13) |

Disabling Hearing Loss: PTA (0.5, 1, 2, 4 kHz) greater than 40 decibels (dB) in adults and hearing loss greater than 30 decibels (dB) in children.

Any level of Hearing Loss: PTA (0.5, 1, 2, 4 kHz) greater than 25 decibels (dB) in adults and children.

|  |
| --- |
| Table 3. Accuracy measures of hearTest smartphone-based audiometry for hearing screening in adults against conventional audiometry by response mode and ear (273 individuals/546 ears) |
| Hearing loss definition / hearTest mode | Sensitivity% (CI 95%) | Specificity% (CI 95%) | PPV% (CI 95%) | NPV% (CI 95%) | Youden Index% (CI 95%) |  |
|  | Left | Right | All | Left | Right | All | Left | Right | All | Left | Right | All | Left | Right | All |  |
| Disabling Hearing Loss |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Self-test | 97.4(91.0;99.7) | 98.8(93.4;100.0) | 98.1(94.6;100.0) | 93.8(89.5;96.8) | 93.7(89.3;96.7) | 93.8(90.9;95.9) | 86.4(77.4;92.7) | 87.1(78.5;93.1) | 86.7(80.9;91.3) | 98.9(96.1;99.9) | 99.4(96.9;100.0) | 99.2(97.6;99.8) | 91.3(86.4;96.1) | 92.5(88.3;96.7) | 91.9(88.7;95.1) |  |
| Test-operator | 100.0 | 98.8(93.4;100.0) | 99.4(96.6;100.0) | 92.3(87.6;95.6) | 90.6(85.5;94.3) | 91.4(88.2;94.0) | 83.9(74.8;90.7) | 81.8(72.8;88.8) | 82.8(76.7;87.9) | 100.0 | 99.4(96.8;100.0) | 99.7(98.4;100.0) | 92.3(88.6;96.0) | 89.4(84.6;94.1) | 90.8(87.8;93.9) |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Any level of Hearing Loss |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Self-test | 100.0 | 98.3(94.1;9.8) | 99.1(97.0;100.0) | 80.8(73.7;86.6) | 79.2(71.9;85.3) | 80.0(75.1;84.3) | 79.6(72.2;85.8) | 78.5(71.1;84.8) | 79.0(74.0;83.5) | 100.0 | 98.4(94.3;99.8) | 99.2(97.1;100.0) | 80.8(74.6;86.9) | 77.5(70.3;84.3) | 79.1 (74.5;83.8) |  |
| Test-operator | 100.0 | 99.2(95.4;100.0) | 99.6(97.7;100.0) | 76.3(68.8;82.7) | 74.7(67.0;81.3) | 75.5(70.3;80.2) | 76.0(68.4;82.5) | 75.2(67.6;81.7) | 75.6(70.4;80.2) | 100.0 | 99.1(95.3;100.0) | 99.6(97.5;100.0) | 76.3(69.6;83.0) | 73.8(66.8;80.9) | 75.1(70.2;79.9) |  |

Disabling Hearing Loss: PTA (0.5, 1, 2, 4 kHz) greater than 40 decibels (dB).

Any level of Hearing Loss: PTA (0.5, 1, 2, 4 kHz) greater than 25 decibels (dB).

PPV= Positive predictive value.
NPV= Negative predictive value.

Youden index (J) = Se + Sp – 1.

|  |
| --- |
| Table 4. Accuracy measures of hearTest smartphone-based audiometry for hearing screening in children against conventional audiometry by response mode and ear (28 individuals/56 ears) |
| Hearing loss definition / hearTest mode | Sensitivity% (CI 95%) | Specificity% (CI 95%) | PPV% (CI 95%) | NPV% (CI 95%) | Youden Index% (CI 95%) |  |  |
|  | Left | Right | All | Left | Right | All | Left | Right | All | Left | Right | All | Left | Right | All |  |
| Disabling Hearing Loss |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Self-test | 100.0 | 100.0 | 100.0 | 100.0 | 96.1(80.4;100.0) | 98.0(89.5;100.0) | 100.0 | 66.7(9.4;99.2) | 83.3(35.9;99.6) | 100.0 | 100.0 | 100.0 | 100.0 | 96.1(88.8;100.0) | 98.0(94.1;100.0) |  |
| Test-operator | 100.0 | 100.0 | 100.0 | 92.0(74.0;99.0) | 96.1(80.4;100.0) | 94.1(83.8;98.8) | 60.0(14.7;94.7) | 66.7(9.4;99.2) | 62.5(24.5;91.5) | 100.0 | 100.0 | 100.0 | 92.0(81.4;100.0) | 96.1(88.8;100.0) | 94.1(87.7;100.0) |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Any level of Hearing Loss |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Self-test | 100.0 | 100.0 | 100.0 | 88.0(68.8;97.4) | 92.3 (74.9;99.0) | 90.2(78.6;96.7) | 50.0(11.8;88.2) | 50.0(6.8;93.2) | 50.0(18.7;81.3) | 100.0 | 100.0 | 100.0 | 88.0(75.3;100.0) | 92.3(82.1;100.0) | 90.2(82.0;98.4) |  |
| Test-operator | 100.0 | 100.0 | 100.0 | 88.0(68.8;97.4) | 80.8(60.6;93.4) | 84.3(71.4;93.0) | 50.0(11.8;88.2) | 28.6(3.7;71.0) | 38.5(13.9;68.4) | 100.0 | 100.0 | 100.0 | 88.0(75.3;100.0) | 80.8(65.6;95.9) | 84.3(74.3;94.3) |  |

Disabling Hearing Loss: PTA (0.5, 1, 2, 4 kHz) greater than 30 decibels (dB).

Any level of Hearing Loss: PTA (0.5, 1, 2, 4 kHz) greater than 25 decibels (dB).

PPV= Positive predictive value.

NPV= Negative predictive value.

Youden index (J) = Se + Sp – 1.