Supporting Hearing Health in vulnerable populations through community care workers using mHealth technologies

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Abstract

Objective: Access to hearing care is challenging in low- and middle-income countries, where the burden of hearing loss is greatest. This study investigated a community-based hearing screening program using smartphone testing by community care workers (CCWs) in vulnerable populations infected or affected by HIV. Experiences of CCWs were also surveyed.

Design: The study comprised two phases. Phase one employed a cross-sectional research design to describe the community-based program. Phase two was a survey design to describe CCW's knowledge and experiences.

Study Sample: Fifteen trained CCWs administered hearing screenings on 511 participants during home-based visits using a validated smartphone application (hearScreen™) during phase one. Diagnostic follow-up assessments included evaluation using the smartphone test (hearTest™), otoscopy and tympanometry. Phase two surveyed the 15 CCW screening experiences.

Results: Referral rates for adults and children were 5.0% and 4.2% respectively. 75.0% of referred participants returned for follow-up diagnostic assessments, 33.3% were diagnosed with hearing loss and referred for further intervention. All 15 CCWs agreed that communities needed hearing services and only 6.6% did not want to continue providing hearing screening.

Conclusion: Trained CCWs can decentralize hearing services to vulnerable communities using smartphone screening incorporating automated testing and measures of quality control.

Keywords: mHealth, community based, HIV and AIDS, smartphone, tele-assisted, vulnerable

Introduction

Hearing loss is one of the most frequently occurring non-fatal disabling conditions, affecting individuals, communities and societies worldwide (World Health Organization 2018). In 2015, approximately half a billion people worldwide were living with a disabling hearing loss, approximately 6 to 8% of the world's population (Wilson, Tucci, Merson, and O'Donoghue 2017). Furthermore, the prevalence of hearing loss is substantially higher in low-to-middle income countries (LMICs) such as in sub-Saharan Africa, which accounts for 9% of hearing loss globally (World Health Organization 2018; World Health Organization 2012). Infectious diseases, like HIV, predispose persons to conductive and sensorineural hearing losses (Ensink and Kuper 2017; Ndoleriire, Turitwenka, Bakeera-Kitaaka, and Nyabigambo 2013).

Studies have demonstrated that even a mild hearing loss, if unidentified, can affect a child's speech and language development, and negatively impact behavior, education and overall well-being (Wenjin et al. 2014). In developing countries where poor literacy levels are high and spoken communication is predominantly used, the effects of a disabling hearing loss can be even more adverse and detrimental than in developed countries (Swanepoel et al. 2010). Early identification of a new or developing hearing loss in one or both ears is crucial in order to minimize the associated negative consequences of hearing loss, and should be followed by appropriate referral for intervention (American Academy of Audiology 2011). Unfortunately, the majority of such populations live in communities where hearing health care services are inaccessible or severely limited (Mulwafu, Ensink, Kuper, and Fagan 2017).

Furthermore, communicable diseases remain one of the primary causes of adult and child mortality in LMICs (Ssengonzi 2009). With a generation of children already orphaned with the loss of one or both parents due to HIV and AIDS within sub-Saharan Africa, the traditional family structure is often no longer in place and many grandparents are left to provide care and support to vulnerable populations (Andrews et al. 2006). Subsequently poverty is deepened within these LMICs due to associated costs during illness as well as after death, exacerbating the already limited access to health care (Andrews et al. 2006). The increased prevalence of hearing loss among HIV-infected individuals, as well as the associated costs for family members of HIV-infected individuals necessitates service delivery models to ensure access to preventative hearing health services.

Evidence suggests that primary health care visits may be the only feasible platform where ear and hearing health services could be accessed by individuals with hearing loss in LMICs (Bogardus, Yueh, and Shekelle 2003; Swanepoel and Clark 2019). Unfortunately many barriers exist to access these services within primary health care settings including costs associated with conventional audiometric test equipment and travelling, as well as time required by patients to attend clinics (Swanepoel et al. 2010; Swanepoel and Clark 2019). Furthermore, there are limited hearing health professionals available in these settings who can offer the required services (Mulwafu et al. 2017). It is estimated that only one audiologist per 0.5 million to 6.25 million people in developing countries worldwide is available; that is, less than one audiologist for every one million people in sub-Saharan Africa (Goulios and Patuzzi 2008; Mulwafu et al. 2017; Windmill and Freeman 2013).

Incorporating telehealth approaches have been proposed as one way in which access to care could be improved and existing barriers overcome in LMIC's (Swanepoel et al. 2010; Swanepoel, Olusanya, and Mars 2010). It offers unique opportunities to enable access to hearing health through smartphone-based mobile health (mHealth) technologies for example (Clark and Swanepoel 2014; Davis and Smith 2013; Swanepoel and Clark 2019). Smartphone hearing screening as well as diagnostic testing using the hearScreen™ and hearTest™ applications have been demonstrated to be valid and appropriate for use in primary health care and community-based settings (Mahomed-Asmail, Swanepoel, Eikelboom, Myburgh, and Hall 2016; Sandstrom, Swanepoel, Myburgh, and Laurent 2016; Swanepoel, Myburgh, Howe, Mahomed, and Eikelboom 2014; Van Tonder, Swanepoel, Mahomed-Asmail, Myburgh, and Eikelboom 2017). Smartphone hearing screening and diagnostic testing offer an inexpensive and mobile alternative to conventional evaluations by utilizing widely available smartphone and headphone technology for time-efficient identification of hearing loss (Louw, Eikelboom, and Myburgh 2017). Furthermore, no significant difference in performance and test results was obtained between conventional (Mahomed-Asmail et al. 2016; Swanepoel et al. 2014) and smartphone audiometry (Sandstrom et al. 2016; Van Tonder et al. 2016).

These technologies also afford advantages that include integrated quality control measures like remote monitoring of environmental noise and test operator performance (Mahomed-Asmail et al. 2016; Swanepoel et al. 2014). These mHealth solutions employ simple user interfaces and automated test sequences that allow minimally trained laypersons such as community care workers (CCWs) to render services in communities (Yousuf Hussein, Swanepoel, Mahomed, and Biagio de Jager 2018; Yousuf Hussein et al. 2016; United Nations Educational, Scientific and Cultural Organization 2017). Community-based services have demonstrated promise as a platform for mHealth-assisted screening (van der Merwe, Mosca, Swanepoel, Glascoe, and van der Linde 2018). CCWs often provide various services for disadvantaged households and could be leveraged for hearing health care services at primary care levels (Yousuf Hussein et al. 2016). By directly visiting households, CCWs improve the accessibility of health services and can ultimately reduce the costs involved (O'Donovan, Verkerk, Winters, Chadha, and Bhutta 2019; Braun, Catalani, Wimbush, and Israelski 2013). Furthermore, by shifting tasks from highly trained personnel to community members, the demands placed on limited ear and hearing health professionals in LMICs are also reduced (Chadha 2013; Yousuf Hussein et al. 2018; Yousuf Hussein et al. 2016).

The potential application and impact of mHealth solutions facilitated by CCWs in vulnerable communities are significant although there has been limited evidence to date for community-based hearing care in sub-Saharan Africa (Chadha 2013; Yousuf Hussein et al. 2016; Swanepoel and Clark 2019). Employing a decentralized approach to service-delivery (Chadha 2013) mHealth may enable more cost-effective and sustainable means of providing ear and hearing health services to vulnerable households in LMICs towards timely referral and follow-up. The current study investigated a community-based programme supporting vulnerable populations affected and infected by HIV and AIDS to identify hearing loss using smartphone screening operated by CCWs. A secondary objective was to describe CCW hearing health knowledge and user experience of the service.

Materials and Methods

Institutional review board clearance was obtained before any data collection commenced. The study included two phases.

Phase 1: Community-based Hearing Detection and Diagnosis

Participants

Participants were selected from a LMIC community in the City of Pretoria, Gauteng Province, South Africa. Convenience sampling was employed to invite CCWs to be trained for inclusion of behavioral pure tone hearing screenings to their home-based services. 15 CCWs agreed to take part in the current study. These CCWs were recruited from local communities within Pretoria by a non-profit organization (NPO) situated in Pretoria, South Africa, to provide various services to disadvantaged households. Each CCW was assigned to approximately 20 households and offered hearing screenings as an additional service during home-based visits within Pretoria.

Non-probability purposive sampling was used to invite 511 individuals who previously received services from CCWs as part of the NPO's initiative to participate in this study. Participants included adults and children (>4 years old) infected or who have family members infected with HIV and AIDS who reside in Pretoria. The above-mentioned participants were included in the current study as the NPO already provided community-based services to these targeted vulnerable populations.

Environment

The study was conducted in the inner City of Pretoria, Gauteng Province, South Africa. Hearing screenings were conducted in the homes of the 511 participants who agreed to take part in the current study. CCWs conducted the hearing screenings in the participant's home in the most suitable room available with the least amount of background noise. In the event that a full diagnostic test was needed; participants were referred to the NPO head office situated in Pretoria where follow-up diagnostic audiometry was conducted by the first author. Diagnostic testing comprised of otoscopy, tympanometry and automated diagnostic air conduction pure tone audiometry using the smartphone hearTest™ application.

Material and Apparatus

Hearing screening was conducted using the hearScreen™ application, version 3.309 (hearX group, Pretoria, South Africa), installed on six Samsung Trend Neo smartphones (Android OS, 4.0) connected to supra-aural Sennheiser HD280 Pro headphones. The hearScreen™ calibration function was used to calibrate the headphones according to prescribed standards (ISO 389-1:1998) adhering to equivalent threshold sound pressure levels determined for this headphone according to ISO 389-9:2009 (Madsen and Margolis 2014). Calibration was performed using a G.R.A.S. RA0039 artificial ear using a RION NL-52 sound level meter complying with ISO 60318-1:2009 and ISO 60318-2: 1998 (Van der Aerschot et al. 2016). The hearScreen™ application employs automated test protocols. A sweep test was performed at the test frequencies of 1, 2 and 4kHz at an intensity of 25dB HL for children and 35dB HL for adults. Noise levels are recorded and monitored by the smartphone application to avoid exceeding maximum permissible ambient noise levels (MPANLs) during testing. A quality index (QI) is recorded, which indicates the quality of tests conducted by the test operator by reflecting the number of false-positive responses obtained by the test operator when a non-stimulus condition is randomly presented to the participant.

Diagnostic assessments included diagnostic audiometry using the hearTest™ smartphone application, version 3.309 (hearX group, Pretoria, South Africa), otoscopy and tympanometry (Katz 2014) which were conducted using a Welch Allyn otoscope and a GSI 38 Auto Tympanometer. The hearTest™ mobile diagnostic testing application, version 3.309 (hearX group, Pretoria, South Africa), was installed on one Samsung Trend Neo smartphone (Android OS. 4.0) and utilized for air conduction threshold pure tone audiometry (Sandstrom et al. 2016; Van Tonder et al. 2017). This application is a self-administered, automated hearing assessment that has been validated to record reliable air conduction hearing thresholds (Van Tonder et al. 2017). Automated audiometry consisted of air conduction testing at 0.5 to 8 kHz starting at an intensity level of 40dB HL until a minimum response level of 10dB. The threshold determination sequence follows the Threshold Ascending method as specified in ISO 82531:1.5. Noise levels were recorded and monitored by the smartphone application to avoid exceeding MPANLs.

Procedures

Smartphone hearing screening. Hearing screenings were conducted by 15 CCWs who provided consent to participate in the study. CCWs involved in this study had no formal training in ear and hearing health care. A five-hour training session was conducted prior to the implementation of the screening programme. The training session was conducted by the first author; a qualified audiologist. The CCWs were trained in general ear and hearing health care, how to administer smartphone hearing screenings and were given a practical session for hands-on experience. Hearing screenings were only conducted if consent/assent had been granted by participants and parents/guardians of participants younger than 18 years of age. Each participant was provided with a simple explanation and demonstration of what the test entails and what is expected of him/her. A CCW, seated behind each participant, instructed participants to raise their hand each time they heard the tone presented. A conditioning tone was presented first in order to ensure that the participant understood the instructions.

The hearScreen™ application makes use of a smart noise-monitoring algorithm. If noise levels exceeded MPANLs; a warning was provided to the CCW who could then move to a quieter room or reduce background noise before continuing the test. Noise levels were automatically recorded by the smartphone application, and testing was completed on the second trial even if noise levels could not be reduced adequately. Once the test was complete, the hearScreen™ application immediately calculated and displayed to the CCW the results at each frequency and an overall "pass" or "refer" result (Figure 1). A random non-presentation of the stimulus is initiated during testing as a test operator QI. If the test operator indicates that the participant heard this stimulus it is flagged as a false-positive response by the operator. This QI score is monitored and a score below 70% is flagged for retraining.

(a) (b) (c)

Figure 1. hearScreen™ user-interface for (a) stimulus presentation, (b) response options, and (c) results page.

Failure to hear a tone at any frequency in either ear constituted a 'refer' result and an immediate rescreen was conducted. If the participant obtained a 'refer' result on the rescreen: he/she was referred for a full diagnostic hearing assessment conducted by the first author within four weeks of the initial screening. Results were communicated directly via text messages to participants and/or parents/guardians of participants younger than 18 years of age. Test results collected by the smartphone application were immediately uploaded to a secure cloud-based server via a mobile network for data management.

Diagnostic follow-up. Diagnostic testing was conducted by the first author within four weeks of the initial screening at the NPO's office in Pretoria. Participants were provided with a short explanation of what each test entails and what is expected of him/her. Testing comprised otoscopy, tympanometry and air conduction threshold audiometry using the hearTest™ application to determine degree and configuration. Testing mode was differentiated between manual and automated depending on the participant's age and ability to use the response button on the device. In the event the participant was unable to respond or hold the device themselves; a test-operator mode was enabled to permit manual testing by the first author. The procedure used for manual testing was similar to that of hearing screening. The first author, seated behind each participant, instructed participants to raise their hand each time they heard the tone presented.

Background noise recorded by the smartphone was monitored throughout testing. A threshold was determined by the minimum intensity at which the participant reliably responded twice. These results, in conjunction with otoscopy and tympanometry, were used to identify the presence of a hearing loss. Results collected by the smartphone application were uploaded to a secure cloud-based server via a mobile network for data management. Once diagnostic testing was completed, if needed participants were referred to their closest tertiary hospital that offered the required medical or audiological services.

Data analysis

Data were extracted from the cloud-based server to an MS Excel spread-sheet for statistical analysis. Results were analysed using descriptive statistics to analyse referral rate, follow-up rate, compliance of the test environment and time proficiency of the hearing screenings. A p value of < 0.05 was used to indicate the level of significance using the Pearson Chi-Square test.

Phase 2: CCW Knowledge of Hearing Health and Screening Experiences

Participants

The 15 CCWs invited to conduct hearing screenings during phase one of the current study were invited to report on their knowledge and experiences of community-based hearing screening by means of two self-administered questionnaires. Questionnaires were administered at the NPO in Pretoria, Gauteng Province, South Africa.

Material and Apparatus

The first questionnaire consisted of 13 questions using a three-point rating scale (1 indicating yes; 2 indicating unsure; 3 indicating no) regarding their knowledge of hearing health care. The second questionnaire was adapted from a previous study and consisted of 10 questions to be answered using a five-point Likert rating scale of 1 indicating strong agreement; 5 indicating strong disagreement (Yousuf Hussein et al. 2016). The second questionnaire surveyed usability, need for services, value to the community, time proficiency and their involvement in the service provided.

Procedures

The two self-administered questionnaires were completed at the NPO's office in Pretoria. CCWs were invited to complete two self-administered questionnaires following the community-based hearing screening programme. Both questionnaires were completed anonymously and took approximately 10 minutes to complete.

Data analysis

Responses from the questionnaires were coded into quantitative data in MS Excel for statistical analysis. Results were analysed using descriptive statistical measures in terms of frequency distribution.

Results

Phase 1: Community-based Hearing Detection and Diagnosis

A total of 511 participants, including 276 adults (mean age 30.4; SD 9.1) and 235 children (mean age 8.7; SD 4.1) were included in this study over a period of eight weeks. Of the 511 participants screened; 61.0% (n = 312) were female and 38.9% (n = 199) were male. Mean test duration recorded for initial screenings, excluding time taken for instructions and capturing of demographic information, was 73.5 seconds (SD 49.9) for children, and 57.9 seconds (SD 37.9) for adults. A total of 30 adults (10.8%) and 31 children (13.1%) failed the initial screening and were automatically rescreened (Table 1). Individuals who obtained a 'refer' result on the initial screening had an average age of 9.3 years (range 2-15 years; SD 4.9) for children, and 34.7 years (range 19-66 years; SD 10.6) for adults. Age demonstrated no significant effect on the initial screening referral rate in adults ($p > 0.05$; Pearson chi-square). Although more female (13%; n = 40) than male (11%; n = 21) participants (adults and children) failed the initial screen, the difference was not significant ($p > 0.05$; Pearson chi-square).

The average age for individuals who referred the rescreen was 9.6 years (range 2-15 years; SD 5.4) for children, and 34.2 years (range 19-46 years; SD 10.6) for adults. The overall referral rate decreased from 10.8% to 5.0% (n = 14) for adults, and 13.1% to 4.2% (n = 10) for children following rescreening after an initial refer result. A QI of less than 70% for conducting the hearing screening was obtained by 46.6% (mean = 49.5%; SD 34.8) of CCWs indicative of retraining required. MPANLs were exceeded at 1 kHz in the left ear in 1.6% and 6.1% of adults and children respectively, and in the right ear in 1.2% and 7.8% of adults and children respectively. However, initial screen and rescreen outcomes were not significantly affected by exceeded noise levels in both children and adults ($p>0.05$; Pearson chi-square). Mean test duration for children was 73.5 seconds (SD 49.9), and 57.9 seconds (SD 37.9) for adults.

A total of 24 (4.6%) participants (range 6-46 years; 14 adults and 10 children) were referred for diagnostic audiometry of whom 18 (75.0%) returned for the follow-up assessment. Mean threshold audiometry (hearTest™) test duration was 672.8 seconds (SD 304.3) for children, and 452.1 seconds (SD 202.2) for adults. No MPANLs were exceeded at any frequency. Six (33.3%) referred participants (n = 6) were confirmed to have hearing loss (Table 2) and referred for further intervention.

Phase 2: CCW Knowledge of Hearing Health and Screening Experiences

Following the screening programme, all CCWs (100%; n = 15) were of the opinion that community members needed hearing health care services (Table 3). 93.3% of CCWs also indicated that hearing loss may affect more individuals than others (Table 3), and 46.6% of CCWs were of the opinion that children with a hearing loss are more likely to perform poorer academically as compared to normal hearing peers (Table 3).

86.6% of CCWs (n = 13) agreed or strongly agreed that hearing screening was quick and easy to administer in adults whilst only 66.6% (n = 10) agreed or strongly agreed that it was easy to administer in children (Figure 2). The majority (60.0%) of CCWs agreed or strongly agreed that community members were positive about receiving this service. Most (60.0%) CCWs strongly agreed or agreed in continuing providing hearing screening as part of their services and only one (6.6%) disagreed (Figure 2).

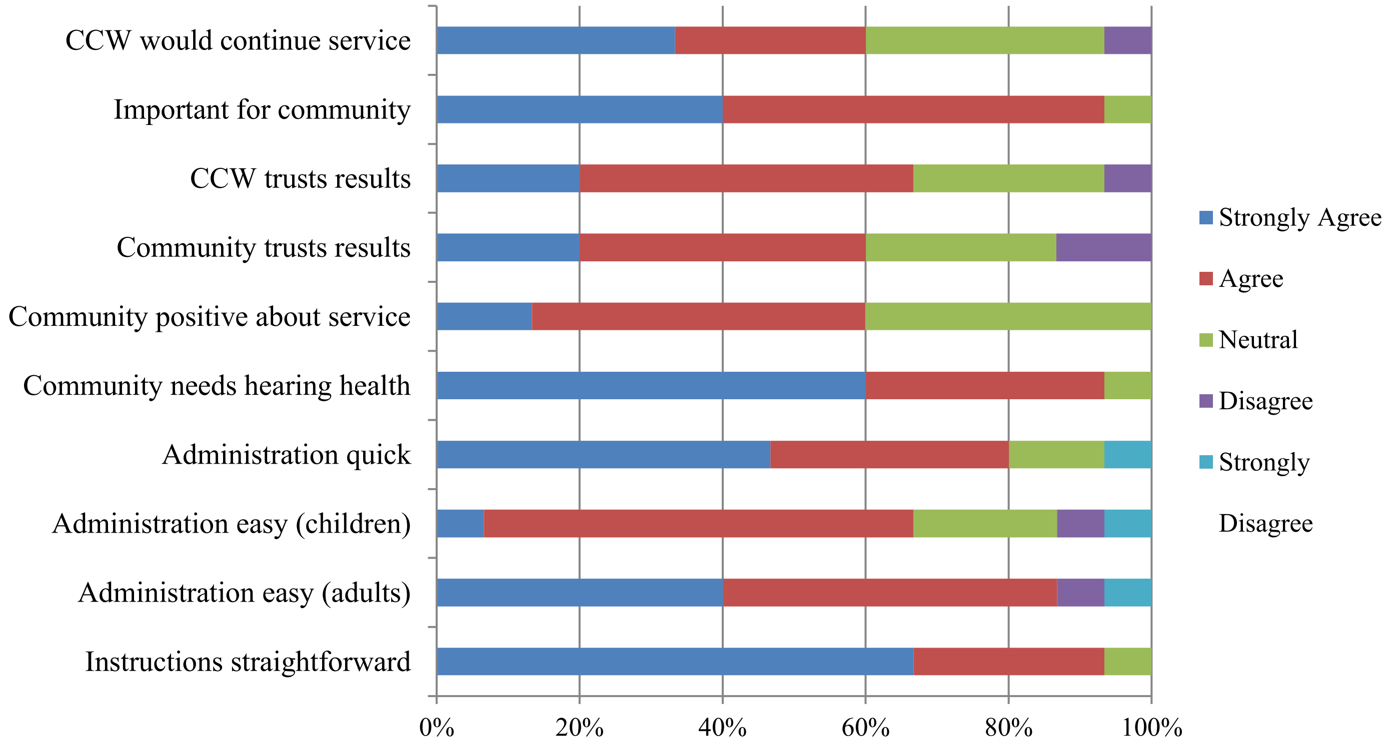

Figure 2. Distribution of CCWs ($n = 15$) responses (%) on experience of screening programme.

Discussion

Empowering underserved communities through the use of mHealth solutions is a novel approach presenting promising opportunities for improved access to primary care services such as ear and hearing health care (Braun et al. 2013). To date, there is limited research on community-based programmes for detection and diagnosis of hearing loss, particularly within vulnerable populations in sub-Saharan Africa (Chadha 2013; Yousuf Hussein et al. 2016). Contextual evidence and strategies are essential when implementing effective programmes aimed at improving access to and awareness of hearing health care within vulnerable communities (Swanepoel and Clark 2019).

This study is the first report on a mHealth assisted hearing detection and diagnosis programme serving a vulnerable community using minimally trained CCWs. The current study also employed CCWs as opposed to community health workers (CHWs) who were utilized in a previous study (Yousuf Hussein et al. 2016). CCWs provide a variety of services to vulnerable community members including donations of food parcels and clothing items as well as various health assessments, as opposed to CHWs who solely provide basic health and medical care to their community. The current study also took place in an urban inner city context and included 235 children for data analysis, as opposed to a previous study which was conducted in a rural setting and only included 108 children (Yousuf Hussein et al. 2016). Furthermore, the current study provided diagnostic follow-up services and referrals for further intervention which was a limitation in a previous study (Yousuf Hussein et al. 2016).

Fifteen CCWs screened a total of 511 community members (235 children; 276 adults) within an eight-week period during regular home-based visits. The majority of community members screened were adults (n = 276), of which majority were female 68.8% (n = 190). This may be due to the home-based visits taking place in the week during work hours (Yousuf Hussein et al. 2016).

The initial referral rate for children (range 2-18 years) using the hearScreen™ application was 13.1%. After an immediate rescreen referral rates dropped to 4.2%. The initial referral rate obtained in adults (range 19-70 years) also decreased, following the immediate rescreen, from 10.8% to 5.0%. Rescreens have been reported to decrease the referral rate in children by half, and are therefore recommended directly after initial screening refers in order to decrease the number of possible false-positive results (American Academy of Audiology 2011). Higher initial referral rates prior to rescreening could be due to a poor understanding of instructions (Yousuf Hussein et al. 2016). CCWs could ensure a better understanding of instructions by repeating or rephrasing instructions provided. Alternatively a translator may also be utilized in the event of a language barrier.

Environmental noise poses a challenge to the successful implementation of hearing screening programmes within uncontrolled environments, such as home visits and schools (American Academy of Audiology 2011). Therefore it is invaluable to monitor noise levels throughout testing as performed in the present study. CCWs were prompted by the application to reduce noise levels before rescreening as far as possible. Although MPANLs were exceeded at one frequency in some cases (left ears: 1.6% cases; right ears: 1.2% cases); no statistically significant effect ($p>0.05$; Chi-square) of MPANLs was observed on screening outcomes.

Age also demonstrated no significant effect on the initial and overall referral rate in adults ($p>0.05$; Chi-square).

A previous study reported a referral rate of 4.3% for children (Swanepoel et al. 2014); which is in line with the referral rate of children (4.2%) in the current study. Another recent study reported a referral rate of 12% for children aged 2-15 using the hearScreen™ smartphone application (Yousuf Hussein et al. 2016). Lower referral rates (4.2%) for children in the current study are likely due to lower environmental noise levels than in the previous study.

Average test duration for initial smartphone hearing screening, excluding time taken for instructions and capturing of demographic information, was 73.5 seconds (SD 49.9) for children; slightly longer in comparison to previous studies which obtained an average of 54.5 seconds (SD 28.3) and 47.4 seconds (SD 20.0) when screening children (Mahomed-Asmail et al. 2016; Yousuf Hussein et al. 2016). The current study obtained an average test duration of less than a minute when screening adults (57.9 s; SD 37.9); similar to that of a previous study which obtained 47.0 seconds (SD 28.8) when screening adults initially (Yousuf Hussein et al. 2016). In comparison to conventional hearing screening, other studies reported an average time of more than two minutes for children; considerably longer than smartphone-based screening (Liew et al. 2009; Wenjin et al. 2014). Shorter test time in the current study may be attributed to the automated screening protocol, compared to manual conventional screening (Mahomed-Asmail et al. 2014). Time efficiency with the smartphone hearing screening application may facilitate screening of larger numbers of individuals over a shorter period of time.

46.6% of CCWs obtained a QI of less than 70% (mean = 49.5%; SD 34.8) when conducting the hearing screenings initially, which signalled the need for retraining. Following retraining, CCWs obtained the required QI and could then continue providing hearing screenings. Further developments to the software are recommended to display any improvements to a test operator's QI throughout a testing period in order to monitor progression following retraining.

A total of 24 participants (14 adults; 10 children) out of the 511 participants screened failed the immediate rescreen and were referred for diagnostic audiometry via text message. Text messaging has been found to be an effective strategy in increasing follow-up return rate

(Liew et al. 2009). Out of the 24 participants referred for diagnostic audiometry; 75% of participants (18/24) returned for diagnostic follow-up assessments indicating an acceptable follow-up return rate. A 70% and higher follow-up return rate is considered a benchmark (Joint Committee on Infant Hearing 2007). Failure to attend follow-up appointments is likely due to diagnostic assessments taking place in the week during work hours, or barriers associated with traveling such as distance and costs involved (Jones, Sherman, and Varga 2005; Yousuf Hussein et al. 2016). Increase in community awareness on the importance of ear and hearing health care, especially within vulnerable communities, may further motivate referred participants to pursue follow-up services.

Average test duration for the diagnostic smartphone application (hearTest™) conducted for follow-up appointments, was 11.21 minutes (672.75 s, SD 304.3) for children and 7.53 minutes (452.1 s, SD 202.2) for adults (excluding instructions). A previous study reported a mean test duration of 6.75 minutes (SD 1.5) when testing adults using the hearTest™ application, similar to that of the current study (Van Tonder et al. 2017). Longer testing times for children in the current study are likely attributed to difficulties with instructions and possible listening fatigue. Listening fatigue may be experienced in children whose hearing is within normal limits, and more commonly in children with hearing loss (Hicks and Tharpe 2002). A total of 6 participants were identified with hearing loss and referred for further intervention. Due to the high prevalence of chronic otitis media as well as conductive hearing loss among HIV-infected individuals, the use of bone conduction audiometry may have been useful to quantify the conductive hearing loss. Investigating the additional value of bone conduction (BC) audiometry to inform referral and treatment in these settings would be beneficial.

Using CCWs supports a decentralised model to create access to hearing health care services (Yousuf Hussein et al. 2018; Yousuf Hussein et al. 2016). In this study CCWs reported that the community was positive about receiving hearing services in their home environments with the majority of CCWs indicating that it was quick and easy to administer in adults (86.6%) and children (66.6%). In a previous study, CHWs also identified screening children as an area in which they required additional experience (Yousuf Hussein et al. 2016). CCWs may therefore benefit from further information and training to ensure quality control and confidence when testing children. The integration of guidelines and informational counselling into the application may also assist CCWs and other generalist health care personnel in screening difficult-to-test populations, as well as in explaining the importance of hearing screening and what the hearing results mean (Yousuf Hussein et al. 2016).

Conclusion

CCWs can be trained to screen for hearing loss during home-based visits in vulnerable populations within LMIC communities. These mHealth approaches, using minimally trained community members, can decentralize access to hearing health services within vulnerable communities, reducing the demands placed on limited ear and hearing health professionals (Yousuf Hussein et al. 2016). Furthermore, integrated quality control measures for environmental noise and test operators allows for remote surveillance within an integrated data management platform. CCWs evidenced a positive attitude towards the smartphone hearing screening programme for vulnerable populations and generally wanted to continue providing screening as part of their regular home-based services. mHealth solutions integrated into community-based screening programmes may provide a cost-effective and sustainable means of providing access to hearing services within vulnerable households, thereby reaching a larger portion of the population.

Acknowledgments

The authors would like to acknowledge and thank Future Families NPO and affiliates for their assistance and contribution toward the research, as well as all participants involved with this study.

The authors would also like to acknowledge and thank the the United States Agency for International Development (USAID), the ResilientAfrica Network (RAN) and University of Pretoria Southern Africa Resilience Innovation Lab (SA RILab) for their generous support and contribution towards funding the research. The contents of this work are solely the responsibility of the authors and do not necessarily represent the official views of the supporting organizations.

Declaration of Conflicting Interest

The authors declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: The hearScreen™ and hearTest™ application is intellectual property owned, patented, and trademarked by the University of Pretoria. The

product is being developed and commercialized by the hearX group (www.hearxgroup.com). The third author's relationship with the hearX Group includes equity and consulting.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The financial assistance of the the United States Agency for International Development (USAID), the ResilientAfrica Network (RAN) and University of Pretoria Southern Africa Resilience Innovation Lab (SA RILab). The contents of this work are solely the responsibility of the authors and do not necessarily represent the official views of the supporting organizations.

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