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Smartphone applications for measuring noise in the intensive care unit: A feasibility study

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ABSTRACT

Purpose: This study aims to explore the suitability of using smartphone applications with low-cost external microphones in measuring noise levels in intensive care units.

Methods: Four apps and two external microphones were tested in a laboratory by generating test signals at five noise levels. The average noise levels were measured using the apps and a professional device (i.e. a sound level meter). A field test was performed in an intensive care unit with two apps and one microphone. Noise levels were measured in terms of average and maximum noise levels according to the World Health Organisation's guidance. All the measurements in both tests were conducted after acoustic calibration using a sound calibrator.

Results: Overall, apps with low-cost external microphones produced reliable results of averaged noise levels in both the laboratory and field settings. The differences between the apps and the sound level meter were within ±2 dB. In the field test, the best combination of app and microphone showed negligible difference (< 2 dB) compared to the sound level meter in terms of the average noise level. However, the maximum noise level measured by the apps exhibited significant differences from those measured by the sound level meter, ranging from −0.9 dB to −4.7 dB.

Conclusion: Smartphone apps and low-cost external microphones can be used reliably to measure the average noise level in the intensive care unit after acoustic calibration. However, professional equipment is still necessary for accurate measurement of the maximum noise level.

1. Introduction

Noise has been a nuisance in the built environment, causing diverse adverse effects on people and communities. One such example is hospitals, where noise levels often exceed the World Health Organisation's (WHO) guidance levels and affect patients' well-being and the productivity of medical staff [1-4]. For instance, de Lima Andrade, et al. [5] recently carried out a systematic review of the literature about noise levels in hospitals and reported that daytime noise levels varied from 37 to 88.6 dBA. The intensive care unit (ICU) is one of the nosiest departments in the hospital due to alarms from medical equipment and noise generated by medical activities [6,7]. Many previous studies have reported that noise levels in an ICU exceeded WHO recommendations for both daytime and night-time [6-13]. For example, average noise levels measured for 24 h from three ICUs in the UK varied from 54.9 to 58.6 dBA. Excessive noise levels in ICUs were still observed in low-income or lower-resourced settings including China [7,14] and the Democratic Republic of Congo [15], and it was a significant burden during the COVID-19 pandemic [7]. Among noise sources, conversation and nursing activities seem to produce higher noise levels than alarms and medical devices [7,16]. This excessive noise in the ICU is reported to affect the wellbeing of patients and healthcare workers, with impacts on patient's sleep [17] and voice disorders among nurses [18]. Thus, Özcan, et al. [19] recently proposed a conceptual framework to help address such noise issues in critical care through multidisciplinary scientific collaboration and medical innovation.

Noise measurement requires professional equipment such as a sound level meter to guarantee precise and accurate results. But sound level meters (Class 1 and Class 2) conforming to standard [20] are expensive and require acoustic knowledge to operate them. Nowadays, the developments of applications for mobile devices have provided non-experts with an accessible and low-cost alternative to measure noise

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levels. In laboratory testing, noise measurement apps for Apple smartphones and tablets with built-in microphones were found to be better than Android devices [21]. While three iOS apps were found to be unreliable compared to the sound level meter [22], certain apps without calibration proved to be reliable in the laboratory conditions [21,23,24]. Consequently, several attempts have been made to measure noise levels using apps outdoors [25], in slaughterhouses [26], and in hospitals [22,27-30]. More recently, apps with external microphones were tested to enhance the accuracy of the noise measurements [31]. Kardous and Shaw [31] highlighted that using external microphones significantly improved the precision of smartphone noise measurements in the laboratory setting. Serpanos, et al. [32] tested apps with and without external calibration of microphones in clinical rooms, but they simulated different noise levels using music. Therefore, the smartphone apps with external microphones were not tested in real environments such as ICUs, and the maximum noise levels were not validated.

This study aimed to explore the suitability of using smartphone apps and external microphones for non-professionals, including healthcare workers, in measuring noise levels in ICUs. First, the apps and external microphones were tested in a laboratory against a Class 1 sound level meter. Second, noise levels were measured in a single-bedded room of the ICU using the apps and external microphones. Both averaged and maximum noise levels were measured in the ICU according to the WHO's guidance.

2. Material and methods

Two tablets (iPad 6th generation with iOS 15.3.1 (hereafter called "iPad 1") and iPad 8th generation with iOS 15.6.1 (hereafter called "iPad 2")) were used. As listed in Table 1, four free iOS apps (Decibel Meter, Decibel X, NIOSH SLM and NoiseLab) were downloaded from the App Store. They were selected from among the available apps designed to measure both the average (L_{Aeq}) and maximum noise levels (L_{AFmax}), based on the highest number of reviews from past users. In addition, two low-cost external microphones (i437L (MicW) and iMM-6 (Dayton Audio)) were selected which were based on performance in the aforementioned study [31].

Before the test, all the apps and microphones were calibrated using a Class 1 sound calibrator (B&K, Type 4230). After the calibration procedures, correction factors, which indicate the difference between the measured level and the reference level, were applied to the apps. The correction factors varied from 0.4 dB to 13.4 dB for the i437L and from −18.7 dB to 6.0 dB for iMM-6. This study consists of two parts: 1) the laboratory test and 2) the field test. The laboratory test was aimed to discover the most appropriate technically viable solution in terms of the accuracy of measured noise levels for the selected apps and microphones. The field test, on the other hand, was designed to see how these solutions behave in the real-life context of the ICUs. The laboratory test was conducted in a reverberation chamber with walls, floor and ceiling that reflect sound. Pink noise with an audible frequency range (20 Hz – 20 kHz) was generated from an omnidirectional loudspeaker (B&K, Type 4292) and subwoofer (Yamaha, SW1181V) at five levels (65, 75, 85 and 95 dB). Unweighted averaged noise levels (L_{eq}) were then measured for 30 s using different combinations. A Class 1 sound level meter (hereafter called "SLM"; Svantek, SV971A) was also used as a reference to determine the accuracies of the tablets. The measurements were repeated five times at each level. A field test was performed in the single-bedded room of the ICU at the Royal Liverpool Hospital, following the recommendations for conducting measurements in hospitals [33]. The dimensions of the room were 5.12 m × 4.98 m × 3.00 m (W × D × H). It had vinyl flooring on the floor, gypsum board or glass windows for the walls, and an acoustic ceiling on the ceiling. The measured reverberation time (T20, averaged between 500 Hz and 1 kHz) for the room was 0.5 s. For the field test, only one external microphone (i437L) and two apps (NIOSH SLM and NoiseLab) were used in our field testing as they produced results closer to the SLM in the laboratory experiment. They also showed significantly smaller correction factors. All the microphones and an SLM were installed in the single-bedded room and they were positioned 0.5 m above the patient's head. They were also placed as far away as possible from hard surfaces such as walls and doors (at least 1 m). Measurements were repeated 10 times, with each measurement lasting for 10 min. All the microphones were calibrated using a sound calibrator and correction factors of 1.9 dB (iPad 1) and 1.1 dB (iPad 2). The sliding door of the room was kept open during the measurements.

Table 1
List of iOS noise measurement apps and external microphones used in this study.

	Name	Developer	
Apps	Decibel Meter	Vlad Polyanskiy	
	Decibel X	SkyPaw Co. Ltd	
	NIOSH SLM	The National Institute for Occupational Safety and Health (NIOSH)	
	NoiseLab (Light)	MicW	
	Model	Manufacturer	Price
Microphones	i437L	MicW	Around £140
	iMM-6	Dayton Audio	Around £40

3. Results

The test results were illustrated using Gardner-Altman plots to present individual readings and effect sizes. The top section reports all individual measurements as a swarmplot to display the underlying distribution. The effect size is reported in the bottom section, with the mean difference between the groups depicted as a black dot and 95% bootstrap confidence intervals calculated from nonparametric sampling of the collected data, shown by the shaded curve and whiskers. Fig. 1 shows the laboratory test result of the iPad 2 with an i437L microphone for four apps at four SPLs. Differences between the SLM and apps were within ±2 dB, varying from −1.1 dB to 1.6 dB. Among the four apps, NIOSH over-measured noise levels, whereas the other three apps under-measured levels. Similar results were obtained from the other tablet with the iMM-6 microphone.

Fig. 2 shows the results of the iPad 2 with an iMM-6 microphone. Differences between the SLM and apps were also within ±2 dB. Most levels from apps were slightly lower than those measured from SLM and the differences between them were statistically significant except for two cases (Decibel Meter at 75 and 85 dB; NIOSH at 65 dB). Similar results were observed from the other iPad across different settings (microphones and apps) and they can be found in Supplementary Figs. S1 and S2.

The results of average and maximum noise levels from the field test are plotted in Fig. 3. The average noise level varied from 53.7 dB to 62.4 dB, while the maximum noise level ranged between 71.7 dB and 93.1 dB. For the average noise level, the differences between the SLM and apps were smaller than 2 dB. In particular, the NoiseLab showed very good agreements with the values from the SLM (<0.5 dB). In contrast, the maximum noise level results from the apps were slightly bigger than the values from the SLM. The differences between the NoiseLab and SLM varied between −0.9 dB and − 3.6 dB, while, those between the NIOSH and SLM ranged from −0.2 dB to −4.7 dB.

4. Discussion

Overall, apps with external microphones performed well in terms of average noise levels. The differences in average noise levels between the SLM and apps were within ±2 dB both in the laboratory and field tests. In particular, NoiseLab with i437L microphone showed very little differences against the Class 1 SLM in the ICU test (≤ ±0.5 dB). When comparing the noise levels in the ICU over a 10-min period, the differences between SLM and NoiseLab (i.e. SLM-NoiseLab) varied from −3.8 to −0.7 dB (please refer to Supplementary Fig. S3) and these differences

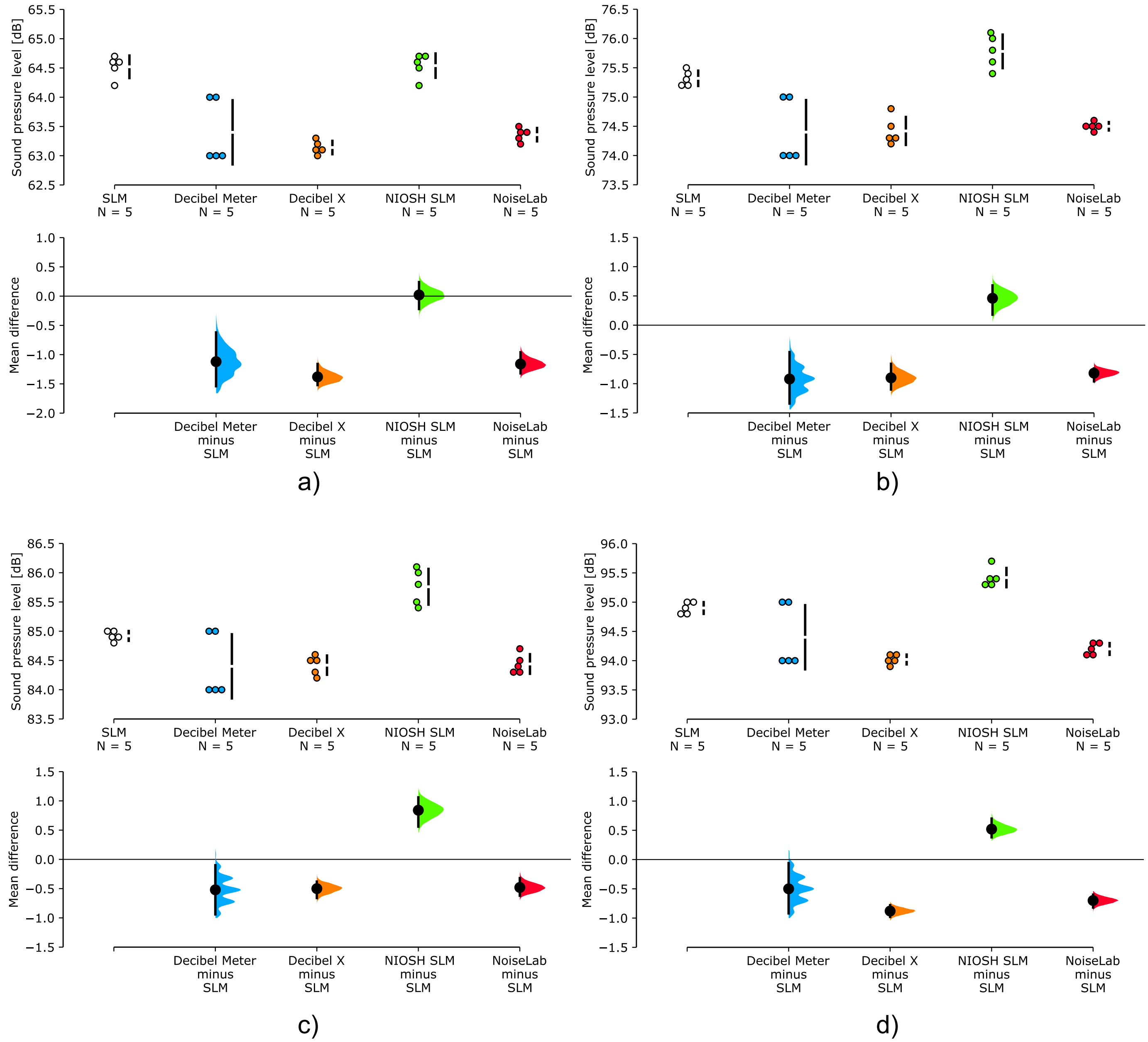

Fig. 1. Laboratory test results: Average noise levels (L_{eq}) of the iPad 2 with i437L microphone across the apps at different noise levels.

were larger than the differences observed in the overall noise levels. This finding indicates that further improvements are necessary for these apps or other future software to deliver more reliable results. Contrary to the average noise levels, the results of maximum noise level from apps exhibited much larger differences in comparison to those of SLM in the field test (± 5 dB). This is possibly due to the signal processing errors in Fast time-weighting detectors. Robinson and Hopkins [34] reported that even Class 1 SLMs had significant variations (up to 3 dB) when considering Fast time-weighted maximum levels. However, the measurement of maximum noise level using apps represents a significant methodological issue because we have demonstrated that the differences between apps and SLM are >3 dB which is a just noticeable difference in loudness. Thus, any readings of noise level from the apps should be used only for illustrative purposes for comparison against the guidelines.

The findings of this study revealed that reliable noise levels can be measured using smartphone apps that are equipped with external microphones. The use of apps might be useful for non-acousticians, such as healthcare workers, who are interested in noise monitoring in ICUs and other hospital settings. However, it should be noted that all the measurement settings in the current study were calibrated using a professional acoustic device (i.e. sound calibrator) before the measurements. Previous acoustic studies [23,31,35], which reported reliable results using smartphone apps, also calibrated microphones and apps before their measurements. In this study, the correction factors of the apps after the calibration were very large, varying from −18.7 dB to 13.4 dB which might cause significant errors. However, the i437L microphone with two apps (NIOSH and NoiseLab) showed relatively low correction factors (<± 2 dB) in both laboratory and field tests, so it can be argued that the noise could be measured without acoustic calibration using this microphone. Nonetheless, the correction factors of this microphone were >3 dB when alternative smartphones were employed. This indicates that in general, these noise measurements cannot guarantee reliable results without acoustic calibration [35,36] even with i437L microphone. Therefore, several noise readings in hospitals measured by using mobile devices such as Apple Watch [3-5] are questionable due to the absence of a calibration procedure. In the future, it would be necessary to

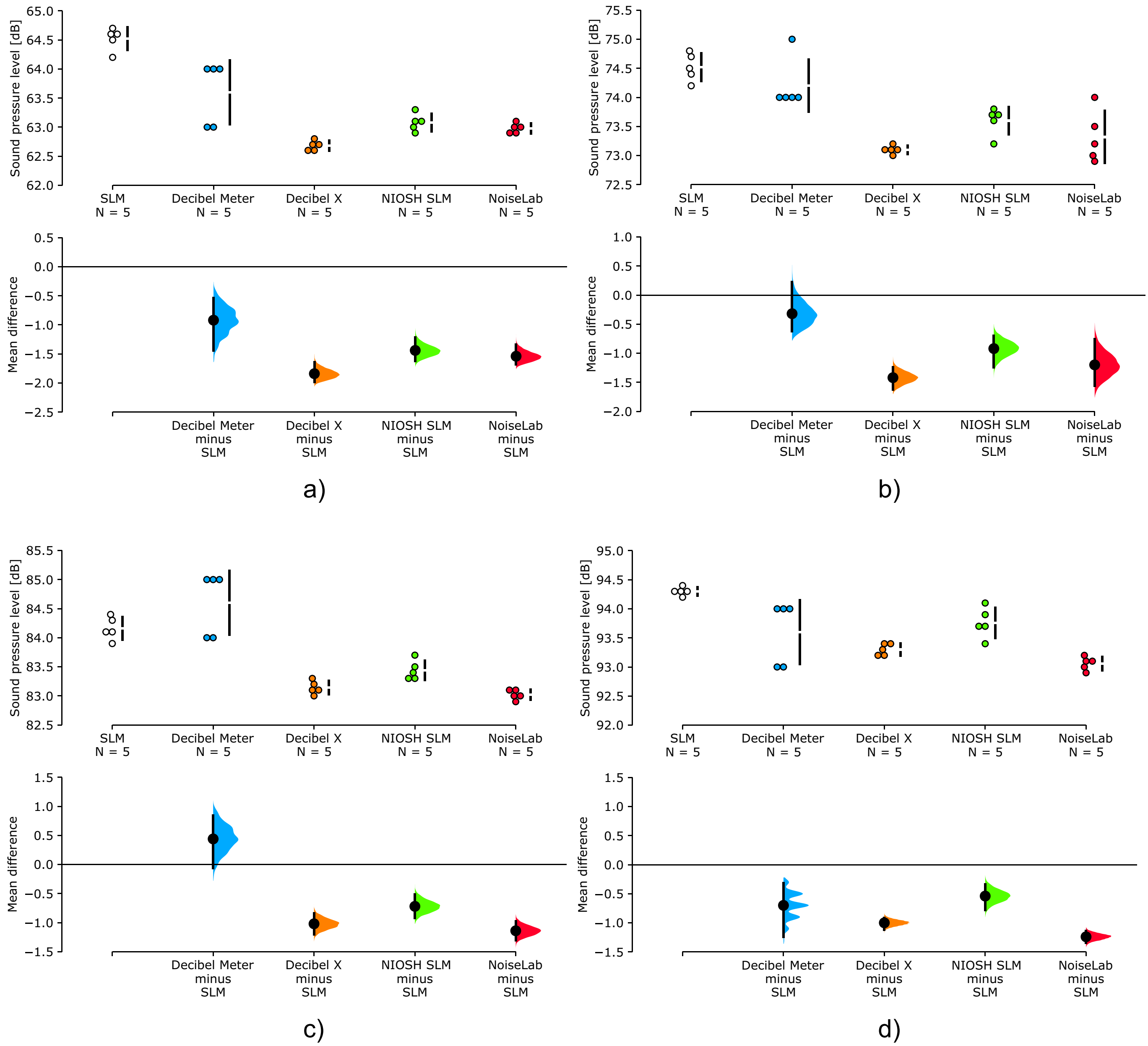

Fig. 2. Laboratory test results: Average noise levels (L_{eq}) of the iPad 2 with iMM-6 microphone across the apps at different noise levels.

enhance the awareness of healthcare workers about the importance of calibration. In addition, maximum noise levels from the apps in the ICU were not precise with ±5 dB differences against the sound level meter. Thus, the readings of maximum noise level from the apps should be used only for illustrative purposes against the guidelines. While measurements taken with low-cost microphones and apps may not be as accurate as the gold standard, they can still serve as useful tools in the daily routines of healthcare workers to track changes in noise levels and their impact on patients. However, for reliable results, it is recommended to either calibrate the devices or seek the expertise of a professional, such as an acoustician.

4.1. Limitations

There are several limitations to consider. First, the field test was conducted only in a single-bedded room for a relatively short duration. Furthermore, there were no instances of severe noise events, such as medication administration, during the test. Therefore, it is necessary to conduct noise measurements over longer periods (e.g., 24 h) in more challenging conditions that include noisy events. Second, the validations of the microphone and apps were performed based on sound pressure level. While comparing time histories is an effective method to validate the accuracy of the measured noise level, most of the apps used in this study do not provide time histories. Among the apps used, only NoiseLab offered this feature.

5. Conclusion

In summary, it was found that app-based measurements performed well in measuring average noise levels, showing ±2 dB in comparison to the measurements with the gold standard sound level meter. The best combination of the app and external microphone showed very high accuracies in the ICU test. In contrast to the average sound pressure level, maximum noise levels from the apps in the ICU were not precise with ±5 dB differences against the sound level meter. These levels of precision from the apps with external microphones were obtained after

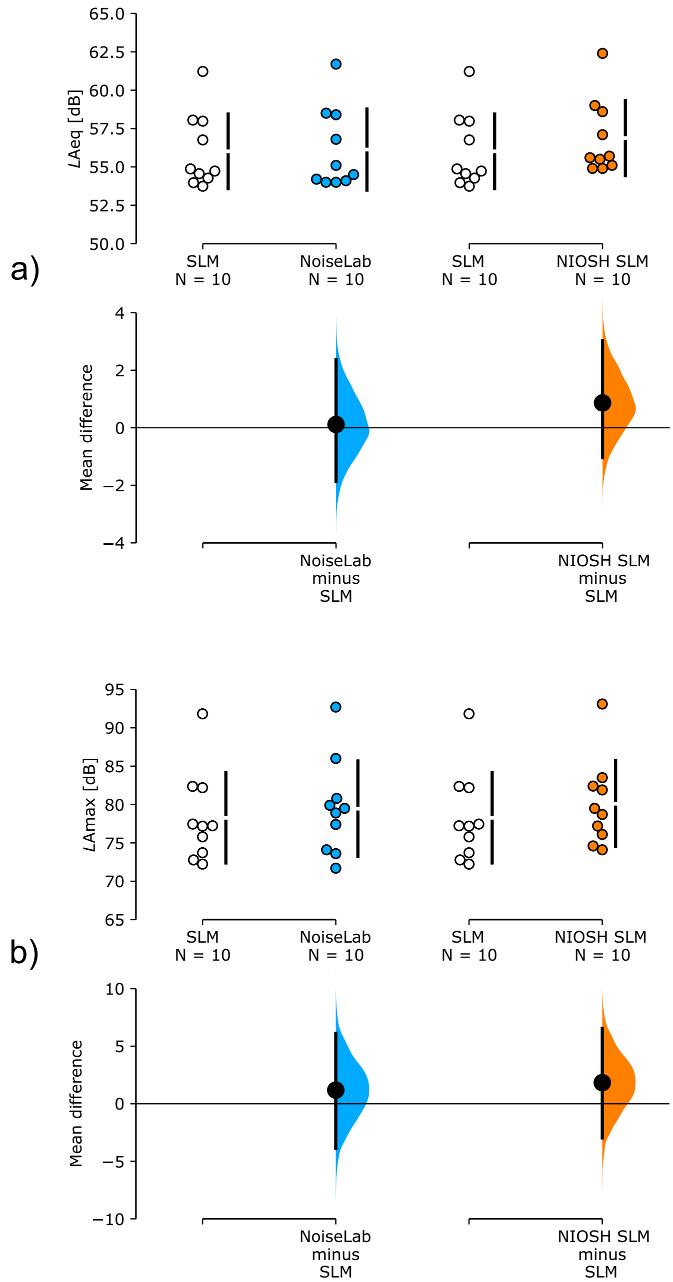

Fig. 3. Field test results: a) average noise level (L_{Aeq}) and b) maximum noise level (L_{AFmax}) from iPad 1 with i437L microphone.

acoustic calibration; thus, it is recommended to calibrate any apps and external microphones before conducting such measurements.

Ethics approval and consent to participate:

Not applicable.

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Not applicable.

Credit authorship contributions statement

PJL and TH designed the study. PJL collected and analysed the data. PJL drafted the first version of the manuscript and TH critically revised the manuscript. All authors read and approved the final manuscript. All authors agree to be accountable for all aspects of the work. All authors read and approved the final manuscript.

Declaration of Competing Interest

TH is in receipt of a Wellcome Trust grant (203919/Z/16/Z). However the authors declare they have no competing interests.

There are no financial conflicts of interest to disclose.

Data availability

All data generated or analysed during this study are included in this published

article (and its supplementary information files).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jcrc.2023.154435.

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