REVIEW ARTICLE

Mobile Applications for Noise Measurement in the Workplace - A Systematic Review

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Received: 21 May 2024 / Accepted: 1 Aug 2024

ABSTRAK

Aplikasi pengukuran bunyi mudah alih amat berpotensi untuk mengantikan alat pengukur bunyi konvensional dalam pengukuran bunyi bising di tempat kerja. Walau bagaimanapun, prestasi aplikasi tersebut dalam mengukur bunyi bising di tempat kerja masih belum dapat dikenalpasti. Oleh yang demikian, tinjauan sistematik ini bertujuan untuk mengenal pasti pelbagai jenis aplikasi pengukur bunyi mudah alih yang mampu mengukur bunyi bising dengan tepat di tempat kerja. Carian literatur telah dijalankan menggunakan pangkalan data PubMed, Scopus, dan Web of Science. Sebanyak 17 kajian telah disenarai pendek daripada 1184 artikel yang diperoleh. Sebanyak 42 aplikasi pengukur bunyi mudah alih telah dikenal pasti (30 aplikasi iOS dan 12 aplikasi Android). Secara umumnya, aplikasi iOS seperti NoiSee (n = 4), SPLnFFT (n = 3) dan SLA Lite (n = 3) adalah aplikasi yang tepat untuk mengukur bunyi bising. Walau bagaimanapun, analisis berdasarkan tempat kajian mendapati bahawa NIOSH SLM (n = 2) adalah aplikasi yang paling tepat dalam mengukur bunyi bising di tempat kerja manakala NoiSee (n = 4) mengukur bunyi bising dengan paling tepat dalam makmal. Aplikasi iOS juga adalah lebih tepat dalam mengukur bunyi bising berbanding aplikasi Android. Mikrofon luaran dapat mengukur bunyi bising dengan lebih tepat berbanding dengan mikrofon dalaman telefon bimbit. Telefon bimbit yang digunakan dalam tempoh lingkungan tiga tahun dapat memberikan ukuran bunyi bising yang paling tepat.

Kata kunci: Aplikasi mudah alih; meter pengukuran bunyi; pengukuran bunyi; tempat kerja

ABSTRACT

Mobile sound level applications have been proposed as potential substitutes for the conventional sound level meters for noise measurement. However, their performance in

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measuring noise remain uncertain in the workplace. As such, the current systematic review aimed to identify the various mobile sound level applications that accurately measured noise in the workplace. Literature search was performed using PubMed, Scopus, and Web of Science databases. A total of 17 studies were included from 1184 retrieved articles. A total of 42 mobile sound level applications were identified (30 iOS and 12 android applications). iOS applications such as the NoiSee (n = 4), SPLnFFT (n = 3), and SLA Lite (n = 3) were the accurate applications to measure noise in general. However, when stratified according to the site of study, the NIOSH SLM (n = 2) was most accurate in measuring noise level in the workplace (i.e., field), while NoiSee (n = 4) was the most accurate application in laboratory setting. iOS applications also outperformed Android applications in accuracy. External microphones measured noise better than internal microphones, and devices within three years old provided the most accurate noise measurements.

Keywords: Mobile applications; noise measurement; sound level meter; workplace

INTRODUCTION

A sound level meter (SLM) is used to measure noise level in the workplace (Department of Occupational Safety and Health 2019). The SLM is designed for real-time measurement of noise levels, typically used as a handheld or fixed device to gauge instantaneous noise levels at a specific location (Department of Occupational Safety and Health 2019). Despite its significance in measuring noise levels, this device has certain limitations. For instance, environmental conditions like wind, temperature, and humidity can influence the precision of noise measurements, introducing variability and complicating the isolation of the noise source's impact (Katalin 2017). In addition, regular calibrations are required for accurate measurements using SLMs, and a lack of calibration or improper calibration can introduce errors (Storey 2015). The need of SLM calibration also incur additional operation costs and burden for the companies, especially the small and medium enterprise (SMEs). Moreover, the correct operation and placement of SLMs require knowledge and skill, and inaccurate measurements may result from the misapplication of the SLM by inexperienced users (Johnson 2023).

In view of the abovementioned limitations and the high penetration rate of smartphone users in worldwide (Craig et al. 2017), various mobile sound level applications have been designed for noise measurement, which could serve as a valuable tool to substitute or supplement the utilisation of SLMs in occupational settings. Mobile sound level applications are software programs designed to transform smartphones into tools for measuring and analysing noise levels (Celestina et al. 2021). Till date, various types of mobile sound level applications have been developed and published, with many of them offering free access in either Google Play Store and/or Apple Store. Such applications include the SPLnFFT (Kardous & Shaw 2014), SoundMeter (Kardous & Shaw 2014), SLA Lite

(McLennon et al. 2019) and NIOSH SLM (Niosh 2023). These mobile sound level applications offer numerous advantages. Firstly, they provide a convenient and easily accessible platform for noise measurement (Nast et al. 2014). Secondly, these applications leverage the inherent portability of mobile devices, enabling users to conduct noise measurements in various environments (Sun et al. 2019). Concerning cost-effectiveness, many sound level applications are either free or significantly more affordable compared to traditional noise measurement equipment like SLMs (Nast et al. 2014). Additionally, these applications typically feature user-friendly interfaces, ensuring easy navigation and operation (Mas'aud et al. 2022). Moreover, they often offer real-time noise monitoring capabilities, providing users with immediate feedback on current noise levels (Abdulgafar 2019). Furthermore, these applications include functionalities for data logging and storage.

Despite the promising functionality of the mobile sound level applications, a majority of these applications are lacking of proper validation in real-world scenarios, in terms of validity and reliability (Murphy & King 2016b; Serpanos et al. 2018; Sun et al. 2019). In addition, given the plethora of mobile sound level applications and mobile devices in the market, occupational health personnel face difficulty to identify the most accurate mobile sound level application that can be used to monitor noise level in their workplace. While some applications have been tested in settings like coffee shops, restaurants, commuter trains, classrooms, hospitals, markets, and streets, their effectiveness and appropriateness in the workplace remain unknown.

In the current review, "workplace" is defined as the area where workers engage with labourious physical job activities and within which these workers might be exposed to excessive noise, including industrial factories and construction site. Having said this, it does not include work areas that only require sedentary job activities. Since the prevalence of occupational noise induced hearing loss among this population is high (Ammar et al. 2022; Ismail & Idris 2023), the availability of a valid and reliable mobile sound level in measuring noise level in these places would be beneficial to preserve the hearing of these workers as well as minimising the healthcare cost for their employers.

Given the lack of evidence-based noise measuring mobile applications and the importance of utilising such application for noise measurement in the workplace setting, the current systematic review aimed to identify the various noise measuring mobile applications that demonstrate high accuracy in noise measurement in the workplace.

MATERIALS AND METHODS

This systematic review had been recorded in the International Prospective Register of Systematic Reviews (PROSPERO CRD42024502619). The conduct of this systematic review was also adhered to the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).

Identifying Relevant Literature

With the assistance of a medical librarian, we identified a comprehensive list of literature in relevance to mobile sound level applications in the workplace. Table 1 described the inclusion and exclusion criteria that were adopted for the systematic review.

The search strategy was developed based on Medical Subject Headings (MeSH) index and other free text terms. As such, our search strategy aimed to identify the intersection between terms related to "sound", "meter", "mobile", "application", and "workplace". Search strategies using a combination of the above terms was documented in the supplementary file. Two investigators (ZQO and AZ) independently performed literature search in the PubMed, Scopus, and Web of Science databases. All retrieved articles were combined into a masterfile using a reference management software. The authors acknowledge that there is a plethora of sound level applications in both Play Store and Apple Store. However, since many of these applications were not studied and analysed empirically through research, they were not included into our review.

TABLE 1: Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Studies that evaluated the effectiveness of mobile sound level application(s) against a standard SLM (i.e., gold standard).	Grey literature.
Studies that were reported in the English language.	Studies that reported on other technologies (e.g., wearable technology) to measure noise, besides mobile phone.
Studies that were conducted in the field and/or laboratory.	

Data Collection Process

After the removal of duplicated studies, we screened and selected studies in two stages. The first stage was an initial screening of titles and abstracts by two independent reviewers (HYC and NAAIS). 25% of the total searches was used as a "training set" for the two reviewers. They were required to independently review these articles based on their titles and abstract and determine whether to include or exclude the articles. This is to establish inter-rater reliability. Once the screening was completed, the two reviewers discussed the search results. Disagreements were resolved via discussion. If the disagreement cannot be resolved, consultation from a third reviewer (SQY) was sought to reach a consensus. In the second stage, the two reviewers (HYC and NAAIS) independently reviewed the full-text articles to determine whether they met the inclusion criteria. Disagreements in regard to the inclusion of articles was discussed. Articles without a consensus agreement and those with questionable eligibility were adjudicated by a third reviewer (SQY).

Data Extraction and Synthesis

Data on the included studies (e.g., the authors, publication years, study countries, study objectives, study designs, sample sizes, study location, study period, name of mobile sound level applications, the types of standard used, statistical analyses and the key findings of the included studies) were documented using descriptive analysis.

Ethics and Dissemination

Since our data did not encompass individual patient information, ethical approval was not deemed necessary.

RESULTS

Literature Search

A systematic search yielded 1184 titles and abstracts. After removing 210 duplicates, 974 unique articles remained. Among these, 922 were excluded based on title and/or abstract review. We thoroughly evaluated 52 full-text articles, and ultimately, 17 met the eligibility criteria. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow diagram was used to illustrate the search decision process of the systematic review (Figure 1).

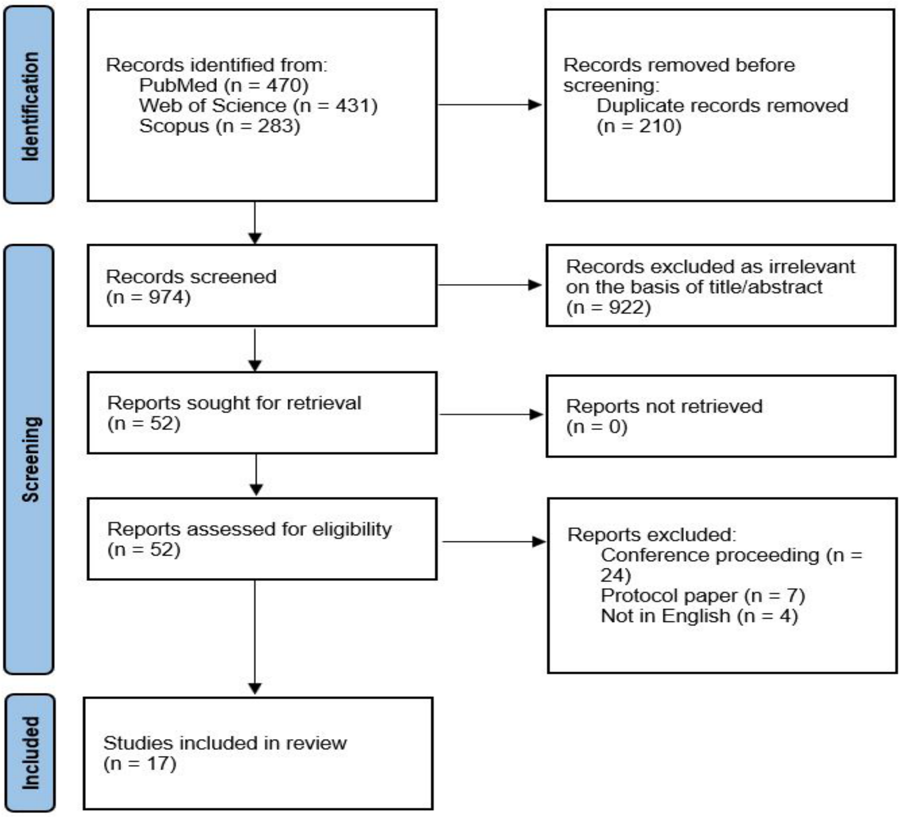

FIGURE 1: PRISMA flow diagram

Characteristics of Included Studies

Out of the 17 articles, 10 (58.8%) were conducted in North America (Celestina et al. 2021; Jacobs et al. 2020; Kardous & Shaw 2014, 2016; McLennon et al. 2019; Nast et al. 2014; Neitzel et al. 2015; Roberts et al. 2016; Serpanos et al. 2018; Sun et al. 2019), five (29.4%) in Europe (Aumond et al. 2017; Crossley et al. 2021; Murphy & King 2016a; Murphy & King 2016b; Ventura et al. 2017), one (5.9%) in the Asia (Sakagami et al. 2019), and one (5.9%) in Africa (Ibekwe et al. 2016). In terms of study design, there were 12 (70.6%) laboratory studies (Aumond et al. 2017; Celestina et al. 2021; Crossley et al. 2021; Kardous & Shaw 2014; Kardous & Shaw 2016; McLennon et al. 2019; Murphy & King 2016b; Nast et al 2014; Roberts et al. 2016; Sakagami et al. 2019; Serpanos et al. 2018; Ventura et al. 2017), three (17.6%) cross-sectional studies (Ibekwe et al. 2016; Jacobs et al. 2020; Murphy & King 2016a), and two (11.8%) utilised a combination of study designs (Neitzel et al. 2015; Sun et al. 2019). Among the five studies that investigated the performance of mobile sound level applications in the field, the common areas included were coffee shop, restaurant, commuter train, classroom, office place, on the street, hospital, market, mining area, and home environments (Table 2).

The number of samples varied from 52 to 1998 individuals. In our review, we have identified 42 mobile sound level applications that measured noise. These consisted of 30 iOS and 12 android applications. The most studied applications were SPLnFFT (n = 6; 14.3%), NoiSee (n = 4; 9.5%), SoundMeter (n = 4; 9.5%), and NIOSH SLM (n = 3; 7.1%). These applications were validated against several gold standard, such as Type 1 SLM (n = 12; 70.6%), Type 2 SLM (n = 3; 17.6%), noise dosimeter (n = 1; 5.9%), and various devices (n = 1; 5.9%). The characteristics of the 17 included studies were tabulated in Table 2 below.

Significant Findings

A majority of the studies (16 out of 17) concluded that the mobile sound level applications were accurate in measuring noise when validated against the gold standards. Specifically, the noise levels (in decibels) measured by the test applications were as close as to those measured via the gold standards. Statistical significance was measured using Pearson's correlation, linear regression, independent t-test, linear mixed model, ANOVA, Repeated measure ANOVA and chi square test.

However, some authors reported that the type of operation being performed, the selection and use of external microphones, distance from a noise source, and environmental factors (e.g., air movement) may all influence the accuracy of the applications' performance (Sun et al. 2019). For most evaluated phones, excellent repeatability has been observed in favourable context-no motion, no wind, microphone clear of friction (Table 2).

Of note, Roberts et al. (2016) concluded that the internal microphones on the tested devices were not able to make noise measurements within 2 dB of a reference noise level. External microphone and source of calibration were needed to make sufficiently accurate noise measurements. Another important finding is that applications on iOS platform is superior to those running on the Android platform

TABLE 2: Characteristics of the included studies

Authors (Years), Countries	Study Objectives	Study Designs	Sample Sizes	Study Location and Study Period	Name of Mobile Sound Level Applications and Types of Standard Used	Statistical Analyses Used	Key Findings of the Studies
Aumond et al. (2017), France	To study the rele-vance and accuracy of mobile phones for measuring urban noise pollution in a large-scale participatory sensing campaign.	Laboratory study	60 samples	- Study location: At 28 locations in Paris. - Study period: September 2013 and September 2014.	- NoiseTube (A) - Cart_ASUR (A) - Gold standard: Type 1 SLM	Pearson's correlation	Sound levels measured with mobile phones correlate very well (r>0.9, p<0.05) with sound levels measured with a class 1 reference sound level meter with a root mean square error smaller than 3 dB(A).
Celestina et al. (2018), USA	To address the com-pliance of smartphone-based systems with international standards for sound level meters.	Laboratory study	Not reported	- Study location: Not reported. - Study period: Not reported.	- NoiSee (I) - Gold standard: Type 2 SLM	Pearson's correlation	- The mobile sound level application and an external microphone can achieve compliance with most of the requirements for Class 2 of IEC 61672/ ANSI S1.4-2014 standard. - The deviations tended to increase towards higher frequencies.
Crossley et al. (2021), UK	To evaluate the effectiveness of a number of iPhone phone applications to accurately measure noise exposure.	Laboratory study	Not reported	- Study location: Sound attenuating room in the Royal South Hampshire Hospital, Southampton, UK - Study period: March 2019	- NIOSH Sound Level Meter (I) - Decibel-Accurate dB Meter (I) - Decibel Meter Sound Detector (I) - Decibel (I) - Audio Spectrum Analyzer db RTA (I) - Decibel Meter master (I) - dB Volume (I) - Decibel X (I) - Decibel Meter with Recorder (I) - Gold standard: Type 1 SLM	Linear regres-sion	- Four of the nine applications were deemed accurate with an R2 value over 0.9. The most effec-tive applications tested was the NIOSH Sound Level Meter with an R^2 of 0.97. The least effective application was the Decibel Me-ter with Recorder with an R^2 of 0.62.

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Ibekwe et al. (2016), Nigeria	- To test the sensitivity and validity of mobile phones as noise measuring devices compared to standard sound level meters.	Cross-sectional study	84 samples	- Study location: Abuja the Federal Capital Territory of Nigeria (across 21 locations, e.g., street, hospital, market). - Study period: January 2014 to February 2015.	- Android-boy1 (A) - Gold standard: type 2 SLM	- Pearson correlation - Independent t-test	- There was a strong correlation (r = 0.9) between the readings measured by the Android-boy1 and SLM. - There was no significant difference in the values (p = 0.12 and 0.58) for measurements made during day and night. - The android-boy-1 performance in this study showed a good correlation and comparative high sensitivity to the Standard SLM (type 2 SLM device)
Jacobs et al. (2020), USA	- To assess the accuracy of measurements made by the NIOSH SLM compared to measurement made by traditional noise dosimeter in five different environments. - To evaluate noise exposures in these environments. - To explore whether the use of an uncalibrated external microphone may improve the accuracy of the measurements made by the NIOSH SLM.	Cross-sectional study	166 samples	- Study location: Five different environments (e.g., coffee shop, restaurant, commuter train, spin class, and office) across four different cities. - Study period: October to December 2017	- NIOSH SLM (I) - Gold standard: Noise dosimeter	- Descriptive analysis - A linear mixed model	- The mean difference in measurements was found to be less than 2.0 dBA (within the accuracy of typical noise measurement instruments) for measurements made in a commuter train, restaurant, and spin class locations. - For the mixed model, the intercept of 53.4 dBA represented the average noise level measured by the smartphone in the office setting. The device variable indicated that, on average, the dosimeters produced a measurement 1.2 dBA lower than the smartphones. The coffee shop, commuter train, restaurant, and spin class were found to be 14.3, 20.0, 26.6, and 38.7 dBA louder than the office setting, respectively. - The NIOSH SLM (without calibration or an external microphone) can be used as an effective screening tool in some settings, particularly when noise levels were stable and exceeded 75 dBA.

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Kardous et al. (2014), USA	- To assess the functionality and accuracy of smartphone sound measurement applications. - To examine the variability of device hardware on the accuracy of the measurements. - To determine whether these applications can be relied on to conduct participatory noise monitoring studies in the workplace.	Laboratory study	700 samples	- Study location: Diffused sound field at a reverberant noise chamber at NIOSH acoustic testing laboratory. - Study period: Not reported	- Adv Decibel Meter 2.0 (I) - Decibel Meter Pro 2.0.5 (I) - iSPL Pro 1.14 (I) - Noise Hunter 1.0.1 (I) - NoiSee 1.0 (I) - Sound Level Meter 1.5 (I) - SoundMeter 3.3.1 (I) - (Real) SPL Me-ter 1.0 (I) - SPL Pro 3.6 (I) - SPLnFFT 4.0 (I) - SPL Meter (A) - decibel Pro (A) - dB Sound Meter (A) - Noise Meter (A) - Gold standard: Type 1 SLM	ANOVA	- The SoundMeter had the best agreement, in A-weighted sound levels, with a mean difference of -0.52 dBA from the reference values. - For A-weighted sound level measurements, Noise Hunter, NoiSee, and SoundMeter had mean differences within 62 dBA of the reference measurements.
Kardous et al. (2016), USA	- To examine the performance and accuracy of the four smartphone iOS applications with two different external calibrated microphones.	Laboratory study	84 samples	- Study location: Diffused sound field at a reverberant noise chamber at NIOSH acoustic testing laboratory. - Study period: Not reported.	- SoundMeter (I) - SPLnFFT (I) - SPL Pro (I) - NoiSee (I) - Gold standard: Type 1 SLM.	ANOVA	- All four applications performed well using both sets of external microphones. - The medians of the differences for the iMM-6 microphones were slightly higher than those measurements made with the i436 microphones.

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McLennon et al. (2019), Canada	- To analyse the accuracy of sound level measurements obtained using various smartphone applications on the iOS and Android platform. - To determine the applicability of the mobile applications in occupational and environmental settings. - To determine the relationship between the type of sound signal used and accuracy of measurement results.	Laboratory study	1000 samples	- Study location: Ryerson University (Canada). - Study period: Not reported.	- Noise Exposure version 2.0.1 (I) - Decibel 10th version 4.3.5 (I) - Sound Meter - Noise Power Level and Decibel Meter version 1.0.0 (I) - SLA Lite - Simple dB Meter version 2.2 (I) - Sound Level Meter (Voice Meter) version 1.8 (I) - Noise Exposure version 2.0.1 (A) - Decibel 10th version 1.4.1 (A) - Sound Meter - Decibel version 1.1.1 (A) - Sound Meter version 3.1.6 (A) - Sound Meter & Noise Detector version 1.2 (A) - Gold standard: Types 2 SLM	RM-ANOVA	- The difference in smartphone platform performance across 60-90 dBA was not clear cut. - Android applications consistently underreported sound level at the 90 dBA. - SLA Lite had the potential to be used as a screening tool in occupational scenarios due to its consistency across all sound levels and low error. - Overall accuracy of these applications was generally inconsistent regardless of phone platform, phone model, sound level, and sound type. - Most of the applications studied were not ready to be used for compliance purposes.
Murphy & King (2016a), Ireland	- To identify the ability of different smartphone models to measure noise ac-curately. - To assess the suita-bility of the applica-tions and the plat-form being utilised to measure noise. - To examine the relationship between smartphone age and measurement accu-racy.	Laboratory study	1472 samples	- Study location: Reverberation room of the University of Hartford, USA. - Study period: 10 days (exact date unspecified)	- SLA Lite Version 1.3 (I) - SPLnFFT version 1.1 (I) - Decibel Meter Pro version 2.05 (I) - UE SPL version 2.1.1 (I) - Sound Meter version 1.6 (A) - Noise Meter version 2.1 (A) - Decibel Pro version 1.4.22 (A) - Gold standard: Type 1 SLM	ANOVA Independent t-test	- Applications on iOS platform was superior to those running on the Android platform. - One of the applications tested (SLA Lite) is within $\pm$1 dBA of true noise levels across 4 different reference conditions: background of 27 dBA, 50 dBA, 70 dBA and 90 dBA. - There was a significant relationship between phone age and its ability to measure noise accurately.

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Murphy & King (2016b), Ireland	- To assess the possibility for smartphone-based noise mapping data to be integrated into the traditional strategic noise mapping process - To test the accuracy of smartphone-based measurement against simultaneous measurements taken using traditional sound level meters in the field	Cross-sectional study	93 samples	- Study location: West Hartford, Connecticut, USA - Study period: 4 hours on 26 September 2015.	- SPLnFFT version 1.1 (I) - Gold standard: Type 1 SLM	Descriptive analysis	- The smartphone-based noise mapping tended to under predict levels of environmental noise relative to the traditional strategic noise mapping process. - In overall terms, there was a ±4 dBA differential at most locations using the two approaches, which was close to the acceptable degree of error of ±2 dBA. - There was very little differential in mean measurement values of 1.4 dBA but the average differential across individual locations was 4.4 dBA, suggesting a relatively high degree of volatility associated with smartphone measurements in the field as compared to traditional SLMs. - The SPLnFFT performed worse when was taken under a more realistic sound environment with a broader range of frequencies that it did in the laboratory.
Nast et al. (2014), USA	· To assess the accuracy of SLM applications by comparing smartphone-based readings with measurements made using Type 1 SLM.	Laboratory study	720 samples	- Study location: Not reported. - Study period: Not reported.	- DB volume version 1.0.5 (DSP Mobile) (I) - Advanced Decibel version 1 (Darren Gates) (I) - SPLnFFT Noise Meter version 3.3 (Fabian Lefebvre) (I) - SPL version 2.6 (Studio Six Digital) (I) - SoundMeter version 3.1 (Faber Acoustical) (I) - Gold standard: Type 1 SLM	Two-way ANOVA	- SoundMeter was the only application that was accurate within 5 dBA across all frequencies and levels for both C- and A- weightings. - Most of the tested applications reported sound levels that were higher than those measured using a calibrated Type 1 SLM. - Non-linearity of outputs of majority of the applications at high level stimuli is suggestive of underreporting of hazardous listening environments.

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Neitzel et al, 2015, USA	- To evaluate the performance of SLMs, personal noise dosimeters and smart devices and applications through in a semi-controlled environment. - To develop and evaluate measurement approaches for continuous, unobstructive in-home monitoring of noise levels.	- Laboratory study - Cross-sectional study	- 176 samples	- Study location: office and home environments in Rockville, Maryland. - Study period: 7 days (exact date unspecified).	- Audio Tools (I) - Gold standard: Type 2 SLM and dosimeter	ANOVA	- Both the SLM and the dosimeter evaluated were appropriate for use in evaluating average A-weighted in-home noise levels continuously. - iPod Touch 4 and 5 devices consistently demonstrated bias in average and variability noise metrics and cannot be recommended for use in extended in-home noise monitoring.
Roberts et al 2016, USA	- To investigate whether iOS smartphones and other smart devices (Apple iPhones and iPods) could be used as reliable instruments to measure noise exposures.	Laboratory study	1998 samples	- Study location: No specific location. - Study period: Not reported.	- NoiSee (I) - SPLnFFT (I) - SoundMeter (I) - Gold standard: Type 1 SLM	- One-way ANOVA - Two-way ANOVA - Independent t-test - Tukey's honest - significant difference (HSD) test	- It was possible to use different iOS smart devices to make accurate noise measurements under certain conditions. However, the internal microphones on the devices tested were not able to make noise measurements within 2 dB of a reference noise level. - External microphone and source of calibration were needed to make sufficiently accurate noise measurements.
Sakagami et al 2019, Japan	- To provide information regarding the accuracy of noise measurement of mobile devices.	Laboratory study	70 samples	- Study location: Anechoic cham-ber in Ueno-higashi area, Toyonaka City, Osaka, Japan. - Study period: Not reported.	- SPL Meter (A) (I) - SLA Lite (I) - Gold standard: Type 1 SLM	Descriptive analysis	- SLA Lite showed good agreement with the type 1 SLM in both iPhone 8 and iPad Pro. - SPL Meter, especially with iPad Pro, was less accurate.

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Serpanos et al 2018, USA	- To determine the accuracy of smartphone sound level meter applications with calibration features across stimulus levels and for ambient room noise measures in the clinical setting.	Laboratory study	52 samples	- Study location: Quiet, unoccupied rooms during active school hours. - Study period: Not reported.	- Analyzer (I) - Sound Level Meter Pro (I) - SPL Meter (I) - Gold standard: Type 1 SLM	Chi-square test	- The accuracy of the three applications to within ±2 dB of the Type 1 SLM was shown along with 95% confidence intervals. - Sound measured with narrowband noise stimuli were significantly more accurate across levels with the calibration feature enabled for Analyzer ($p = 0.02$) and Sound Level Meter Pro ($p = <0.001$). SPL Meter measuring narrowband noise was accurate at 40 to 100 dB with or without calibration. - Using white noise stimuli, most of the measures for Analyzer were inaccurate without calibration. Analyzer was significantly more accurate at 50 to 100 dB with calibration ($p = 0.02$). Sound Level Meter Pro and SPL Meter measured to white noise at 40 to 100 dB were accurate with or without calibration
Sun et al 2019, USA	- To evaluate the accuracy of the NIOSH SLM using a jumbo drill as a noise source. - To examine applications performance in both the laboratory and the field.	Laboratory study	390 samples	- Study location: Hemi-anechoic chamber at the NIOSH Pittsburgh Mining Research Division and an underground metal mine. - Study period: Not reported.	- NIOSH SLM (I) - Gold standard: Type 1 SLM	- Independent t-test - Mixed effect generalised linear model	- The average sound levels measured by the NIOSH SLM were within ±1 dBA of the reference device both in the laboratory and field. - The type of operation being performed, the selection and use of external microphones, distance from a noise source, and environmental factors (e.g., air movement) may all influence the accuracy of the application's performance.

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Ventura et al. (2017), France	To evaluate the mobile phones performance in measuring ambient noise and individual exposure to noise pollution.	Laboratory study	Not reported	- Study location: No specific location. - Study period: Not reported.	- Ambiciti (A) - Gold standard: Type 1 SLM	Linear regressions	- Estimated biases between the raw phone measurements and the SLM readings ranged from -32.5 to 6.9 dB(A). - Nevertheless, for most evaluated phones, excellent repeatability haf been observed in favourable context-no motion, no wind, microphone clear of friction—as well as quite linear responses for levels in the 45 to 75 dBA range.

(I) = IOS; (A): Android; SLM: sound level meter; RM-ANOVA: Repeated Measures Analysis of Variance; dBA: A-weighted decibel

(Murphy & King 2016b). Additionally, there is a significant relationship between phone age and its ability to measure noise accurately (Murphy & King 2016b). Some applications performed worse when taken under a more realistic sound environment with a broader range of frequencies that it did in the laboratory (Murphy & King 2016a) (Table 2).

Among the included studies, four mobile sound level applications had been proven to be accurate in measuring noise in general, these included NoiSee (n = 4) (Celestina et al. 2021; Kardous & Shaw 2014; Kardous & Shaw 2016; Roberts et al. 2016), SPLnFFT (n = 3) (Kardous & Shaw 2016; Murphy & King 2016a; Roberts et al. 2016), and SLA Lite (n = 3) (McLennon et al. 2019; Murphy & King 2016b; Sakagami et al. 2019). However, when stratified according to the site of study, the NIOSH SLM (n = 2) (Jacobs et al. 2020; Sun et al. 2019) was the most accurate mobile sound level application in measuring noise level in the workplace (i.e., field), while NoiSee (n = 4) (Celestina et al. 2021; Kardous & Shaw 2014; Kardous & Shaw 2016; Roberts et al. 2016) was most accurate in a laboratory setting. Of note, the mobile phone used to install these applications were 1-8 years old. Most of the mobile devices that demonstrated accuracy in noise measurement only aged three years old (n = 10) (Ibekwe et al. 2016; Kardous & Shaw 2014, 2016; McLennon et al. 2019; Murphy & King 2016b; Nast et al. 2014; Roberts et al. 2016; Sakagami et al. 2019; Serpanos et al. 2018; Ventura et al. 2017) (Table 3).

DISCUSSION

The current systematic review found three

TABLE 3: Mobile applications proven to be accurate in measuring noise in each study

Authors	Mobile Sound Level Applications Proven to Be Accurate in Each Study	Availability in Apple Store/ Play Store*	Microphone Setting	Mobile Phone(s) Used (Age of Phone at the Time of Study)	Proven Useful In
Aumond et al. (2017)	Cart_ASUR	Not available	Internal	HTC One X (4 years)	Laboratory
Celestina et al. (2018)	NoiSee	Apple Store	External	iPhone 6 (4 years)	Laboratory
Crossley et al. 2021	NIOSH SLM Decibel-Accurate dB Meter Decibel Meter Sound Detector Decibel	Apple Store Not available Apple Store Not available	Internal	iPhone 6 (6 years)	Laboratory
Ibekwe et al. (2016)	Android-boy1	Not available	Internal	Samsung Galaxy Note 3 (3 years) Nokia (model not reported) Tecno Phantom Z (1 year)	Field
Jacobs et al. (2020)	NIOSH SLM	Apple Store	Internal	iPhone 6 (6 years) iPhone 6 Plus (6 years) iPhone 6S (7 years) iPhone 7 (4 years) iPhone 7 Plus (4 years)	Field
Kardous et al. (2014)	SoundMeter Noise Hunter NoiSee	Not available Not available Apple Store	Internal	iPhone 3GS (5 years) iPhone 4S (3 years) iPhone 5 (2 years) iPad 4th generation (2 years)	Laboratory
Kardous et al. (2016)	SoundMeter SPLnFFT SPL Pro NoiSee	Not available Apple Store Not available Apple Store	External	iPhone 5S (3 years) iPhone 6S (1 year)	Laboratory
McLennon et al. (2019)	SLA Lite	Apple Store	Internal	iPhone 4S (8 years) iPhone SE (3 years) iPhone 5S (6 years) iPhone 6 (5 years) iPhone 6 Plus (5 years)	Laboratory
Murphy & King (2016b)	SLA Lite	Apple Store	Internal	iPhone 4 (6 years) iPhone 4S (5 years) iPhone 5 (4 years) iPhone 5S (3 years) iPhone 5C (3 years) iPhone 6 (2 years) iPhone 6 Plus (2 years)	Laboratory

continued...

...continuing

Murphy & King (2016a)	SPLnFFT	Apple Store	Internal	iPhone (model not reported)	Field
Nast et al. (2014)	SoundMeter	Not available	Internal	iPhone 4S (3 years)	Laboratory
Neitzel et al. (2015)	None	NA	NA	NA	NA
Roberts et al. (2016)	- SoundMeter - NoiSee - SPLnFFT	- Not available - Apple Store - Apple Store	External	- iPhone 4 (6 years) - iPhone 4S (5 years) - iPhone 5S (3 years) - iPod 5G (4 years)	Laboratory
Sakagami et al. (2019)	SLA Lite	Not available	Internal	- iPhone 8 (1 year) - iPad Pro (3 years)	Laboratory
Serpanos et al, (2018)	- Analyzer - Sound Level Meter Pro - SPL Meter	- Not available - Not available - Apple Store	Internal	iPhone 6S (3 years)	Laboratory
Sun et al. (2019)	NIOSH SLM	Apple Store	External	- iPhone 5S (6 years) - iPhone 6 (5 years) - iPhone 6S (4 years)	Laboratory and field
Ventura et al. (2017)	Ambiciti	Not available	Internal	OnePlus One (3 years)	Laboratory

key factors influencing the accuracy of mobile applications in measuring noise, including the operating system on which the applications are running, the type of microphone used and the age of the mobile phones.

The accuracy of mobile sound level applications on iOS compared to Android could be largely attributed to the stability and consistency of software and hardware within the iOS ecosystem (Eliza 2024). Apple's control over both hardware and software ensures stable and high-quality application programming interfaces (APIs) for developers, making it easier to create accurate noise measuring applications (Knowledge Hub Media 2023). Besides this, the limited number of iOS devices allows developers to spend more time on calibration and optimisation, ensuring consistent performance across all models (Sigma 2023). In contrast, Android's diverse hardware landscape, with various manufacturers implementing APIs differently, creates challenges for developers. This variability often results in inconsistent application accuracy across different devices. Additionally, the quality control and applications review processes play a significant role in the reliability of noise measuring applications (Simon 2024). Apple's App Store has stringent review standards, ensuring a high level of quality for all applications, including those for noise measurement. Applications that do not meet these standards are likely to be rejected, leading to a higher overall quality of available apps. On the other hand, the Google Play Store's more lenient review process allows a broader range of applications, which can result in a wider variance in application quality and accuracy (Simon 2024). Furthermore, Apple's high standards for built-in microphones, consistent across all devices, provide a reliable foundation for accurate sound measurements (Studio Six Digital 2023). In contrast, the quality of microphones in Android devices varies greatly, contributing to inconsistencies in applications performance.

External microphones tend to be more accurate than internal microphones for measuring noise on smartphones due to their superior design and quality (Kardous & Shaw 2016). This is because external microphones are specifically engineered for high-quality audio recording and sound measurement, featuring advanced components such as high-quality diaphragms and preamps (Synco Audio 2023). These components enable external microphones to capture a broader range of frequencies. In contrast, internal microphones are optimised for general-purpose use, such as voice calls and commands, and are designed to prioritise human speech frequencies (Marshall 2017). The compact and cost-effective design of smartphones imposes limitations on the internal microphones, affecting their performance across the full spectrum of sounds. Moreover, external microphones offer better noise isolation, positioning flexibility, and advanced signal processing capabilities (Harkomal et al. 2023). They often come equipped with features like windshields, shock mounts, and directional pickup patterns that help to isolate the microphone from ambient noise and vibrations, significantly enhancing noise measurement accuracy. External microphones can also be optimally positioned for specific noise measurement needs, ensuring unobstructed sound capture. Furthermore, high-end models include built-in signal processing that reduces noise and improves clarity before the audio signal reaches the smartphone (Hollyland 2023). In contrast, internal microphones are fixed within the smartphone, making them more prone to picking up internal noises and limiting their ability to accurately capture sound from various angles and distances. Additionally, the digital signal processing applied within the smartphone can introduce artifacts, further reducing the accuracy of noise measurements.

The accuracy of noise measurement on smartphones can be significantly impacted by the age of the device, primarily due to hardware degradation, software compatibility issues, and technological advancements (Murphy & King 2016b). Over time, the microphone components within a smartphone are susceptible to wear and tear, resulting from exposure to dust, moisture, and general usage (Khevna 2022). This degradation often leads to a reduction in microphone sensitivity and an increase in background noise, ultimately compromising the accuracy of sound measurements. Additionally, older phones may suffer from diminished battery performance, which can affect the overall functionality of the device, including the performance of audio components (Apple Support 2024). Fluctuations in power supply can further contribute to inconsistent microphone performance, leading to unreliable noise measurements. Moreover, software compatibility and updates play a crucial role in the accuracy of noise measurement on aging smartphones (Cory 2024). As devices age, they may not receive the latest operating system updates, which can result in compatibility issues with newer applications that rely on updated APIs and software optimisations for optimal performance (Cory 2024). Furthermore, developers tend to optimise their applications for the latest hardware and software environments, which may render newer versions of noise measurement applications incompatible or suboptimal on older phones. In contrast, newer smartphones boast improved microphone technology, featuring better sensitivity, wider frequency range, and advanced noise-cancelling capabilities, all of which enhance their accuracy in noise measurement tasks (MIT Technology Review 2020). Additionally, modern smartphones come equipped with more powerful processors and better digital signal processing capabilities, enabling more accurate and real-time noise measurement compared to their older counterparts, which may struggle to keep up with the processing demands of advanced noise measurement applications, resulting in delays or inaccuracies (MIT Technology Review 2020).

Strengths and Limitations

To our knowledge, this is the first review focused on the accuracy of mobile sound level applications in measuring noise. One strength of this review is its comprehensive coverage of the applications, detailing the types of microphones, the mobile phones used, and the availability of the applications on the Apple Store and Google Play Store, enabling future replication of the studies. Another notable strength is that we included only studies that validated the mobile sound level applications against a gold standard (e.g., Type 1 SLM, Type 2 SLM, and dosimeter), ensuring the validity of these applications. However, the review has several limitations. Firstly, the inclusion of laboratory studies is a limitation since many of these studies assessed the accuracy of mobile sound level applications in controlled, quiet environments that do not replicate the varied noise conditions of real workplaces. Secondly, the assessment of bias in these laboratory studies is difficult due to the lack of an appropriate bias assessment tool for such design. Thirdly, the wide range of mobile sound level applications and the extensive statistical analyses performed make it challenging to directly compare the results.

Study Implications

The current systematic review offers several significant implications. Firstly, by encompassing all available mobile sound level applications, it provides a thorough and comprehensive evaluation of the existing and published applications. This inclusive approach ensures that no important applications is excluded, giving a complete overview of the tools available in the market. This extensive analysis helps to identify best applications, offering valuable insights for developers and occupational health personnel. Additionally, the findings from this review can aid in the development of policies and standards for mobile sound level applications. Regulatory bodies and authorities, such as the Department of Occupational Safety and Health can use the review to set benchmarks for accuracy, reliability, and usability of mobile sound level applications, which could complement the conventional SLMs. For end-users, especially those unfamiliar with technical details, the review serves as an educational resource, helping them to understand the capabilities and limitations of various mobile sound level applications, thus guiding them in selecting the most appropriate tool for their needs.

CONCLUSION

The NIOSH SLM is the most accurate mobile sound level application in real workplace settings, while the NoiSee has demonstrated high accuracy in noise measuring in laboratory environments. iOS applications generally outperform Android applications in accuracy. External microphones provide better noise measurement than the internal microphones of mobile phones. Additionally, mobile phones that are within three years old tend to offer the most accurate noise measurements.

ACKNOWLEDGEMENT

The authors express their gratitude to the Faculty of Medicine of the National University of Malaysia for authorising the publication of this review.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable

CONSENT FOR PUBLICATION

Not applicable

AVAILABILITY OF DATA AND MATERIALS

Not applicable

COMPETING INTERESTS

The authors declare that they have no competing interests

FUNDING

The current systematic review is not funded.

AUTHORS' CONTRIBUTIONS

SQY, ZQO, NAAIS, HYC, and AZ contributed to the development of the background and design of the study and planned the output of the research. SQY developed the search strategy design. SQY prepared the manuscript. ZOQ, NAAIS, HYC, and AZ reviewed the manuscript. All the authors read the paper and approved the final version of this manuscript.

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