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JASA ARTICLE

Evaluation of a wearable consumer noise measurement device in a laboratory setting

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ABSTRACT:
Exposure to noise occurs throughout daily life and, depending on the intensity, duration, and context, can lead to hearing loss, disturbed sleep, decreased academic achievement, and other negative health outcomes. Recently, smartwatches that use the device's onboard microphone to measure noise levels were released. This study evaluated the accuracy of these smartwatches in a controlled laboratory setting. For broadband pink noise, a total of 11 441 measurements were collected. The results showed that, on average, the smartwatch reported 3.4 dBA lower than the reference system on average. For the octave-band, a total of 18 449 measurements were collected. The smartwatch measured lower than the reference microphone from the 125 Hz to 1000 Hz octave bands, were somewhat in agreement at 2000 Hz, measured higher sound pressure levels than the reference microphone at 4000 Hz, and then lower at 8000 Hz. Despite not meeting the ANSI criteria for sound level meters, in some cases, these smartwatches still provide a reasonable degree of accuracy and have the potential for use in studies that require the measurement of personal noise exposure over an extended period.

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I. INTRODUCTION

Exposure to noise (i.e., unwanted sound) is ubiquitous in both occupational and non-occupational settings. Although efforts have been made to reduce occupational exposure to noise, many workers in the mining, forestry, agricultural, resource extraction, construction, and other industries are still exposed to noise greater than 85 dBA over an eight-hour workday, which is hazardous to human hearing. Approximately 12% of the U.S. working population has hearing difficulty, and about 24% of the hearing difficulty among U.S. workers is caused by occupational exposures (NIOSH, 2021). The most significant levels of hearing loss are found in workers employed in resource extraction, agriculture, and manufacturing sectors (Masterson *et al.*, 2015). Although efforts have been made to assess occupational noise exposure, Cheng *et al.* (2018) noted in their meta-analysis of occupational noise data that 78% of the occupational groups in the study had moderate to high heterogeneity in their exposure estimates. This was primarily due to the limited exposure information for these groups.

In addition to occupational exposures, a worker can experience significant exposure to noise outside of the workplace, which can increase their risk of hearing loss. Therefore, greater attention has recently been given to hazardous noise exposure in non-occupational settings. In some cases, such as concerts, exercise classes, and sporting events, the overall exposure to noise can be much greater than what is encountered in the workplace, despite the shorter duration of exposure (Carroll *et al.*, 2017; Jacobs *et al.*, 2020; Murphy *et al.*, 2018; WHO, 2021). Environmental noise exposure is more challenging to characterize than occupational exposure because of the near-infinite locations and activities that contribute to a person's environmental exposure. As the United States and other countries transition from manufacturing-based to service-focused, and now to "gig-" based economies, the line between occupational and non-occupational exposures will continue to blur. At the same time, workers will find themselves in jobs where access to occupational health professionals is limited or non-existent.

There has been considerable interest in using onboard microphones on smartphones and other smart devices to measure noise levels. For example, Kardous and Shaw (2014) were the first to systematically evaluate the accuracy of smartphones to measure noise levels in a controlled setting. Roberts *et al.* (2016) found that including inexpensive

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and commercially available 3.5 mm microphones that could be calibrated with a standard field calibrator greatly increased the accuracy of the measurements made by iOS devices. These results were confirmed in follow-up studies (Kardous and Shaw, 2016; Roberts and Neitzel, 2017). The National Institute for Occupational Safety and Health (NIOSH) released a sound level meter (SLM) app for iOS that was evaluated by Sun *et al*. (2019) and Jacobs *et al.* (2020). The app was found to provide reasonably accurate A-weighted sound level measurements even without a calibrated external microphone.

Although smartphone apps have increased the availability of devices that can measure noise and provide recommendations for people to limit or mitigate their noise exposure, they have several inherent limitations. The first is that many people carry their phones in their pocket or bag most of the day, which attenuates the levels of noise presented to the device, leading to an artificially low measurement. In a similar vein, the smartphone's microphone may be impeded by a protective cover, which could also result in attenuated noise levels. In addition, for many apps, a person must actively open, and keep open, the noise-measuring app to make a noise measurement, which typically will not occur unless the person already believes that they are exposed to hazardous levels of noise. In certain environments, such as while on mass transit or in an exercise class, a smartphone may be too unwieldy for actively measuring noise exposure because of competing demands for the users' hands (e.g., balancing and/or holding handles and rails). These limitations are intrinsic to the design of the smartphones and are very similar to the limitations encountered when an SLM is used to measure a person's noise exposure over an extended length of time.

Wearables (such as smartwatches or fitness bands) are more comparable to noise dosimeters that are used to measure noise exposure over an extended time period and eliminate the need to hold a smartphone while making a measurement. Recently, Apple Inc. announced that its Apple Watches are able to measure noise exposure and alert a user when they are being exposed to hazardous levels of noise. Although this feature is potentially useful, no published or publicly available studies to date have systematically evaluated the accuracy of noise measurements made by the Apple Watch or other wearable consumer devices with noise measurement capabilities. Furthermore, the Apple Watch is the first commercially successful wearable to include noise measurement, and its performance is potentially indicative of the measurement capabilities of this class of products. The goal of this study was to conduct a preliminary evaluation of the accuracy of the Apple Watch in a controlled laboratory setting under ideal operating conditions. Although this study specifically evaluated the Apple Watch, the procedures developed and applied here could be used to evaluate other similar devices.

II. METHODS

In total, eight Series 6 Apple watches were tested in this study. All watches were updated to the latest version of WatchOS (6.1 at the time of testing) before the sampling began. Sound levels were measured using the default "Noise" application provided on the watches, which uses the watch's internal micro electro-mechanical systems (MEMS) microphone. This type of microphone is found in smartphones and is suitable for acoustic sensors (Djurek *et al.*, 2019). The measurements were then extracted using an internally developed Noise Export app (Air Force). Measurements made by the watches and the reference system were matched based on the timestamp for each measurement. When sound levels were above 80 dBA, the watches integrated measurements over a 5-s period, otherwise the measurements were integrated over 30-s. All data were compiled in Microsoft Excel (Microsoft, Redmond, WA) and transferred to STATA 16 (StataCorp, College Station, TX) for analysis.

Sampling was conducted at the NIOSH Acoustic Testing Facility (ATF) in Cincinnati, Ohio. The ATF consists of a reverberant sound chamber (12 ft × 12 ft × 8 ft) with a control room and microphones/speakers that can be monitored from the control room. The reverberant chamber used for this study ensured that a diffuse (uniform noise) sound field was generated within the chamber, meaning that the location, orientation, or size of the smartwatches did not influence the study results. The smartwatches were placed on their chargers and the chargers were mounted on a metal stand approximately 4 feet high in the center of the chamber (supplemental Fig. 1[1]). This was done to assess measurement accuracy in a diffuse field of sound and did not account for any reflection or attenuation that may result from the watch being mounted on a user's wrist. Sound was generated through three JBL XRX715 two-way loudspeakers using SigPro 1.5.1 software (VIacoustics, Austin, TX), and sound levels were measured through the Trident 8.9.4 Multi-Channel Acoustic Analyzer Software using a Larson Davis 2560 1/2-in. random incidence microphone (Larson-Davis, Depew, NY) and National Instruments PXIe 4464 data acquisition boards (National Instruments, Austin, TX). The above system consisting of the type 1 microphone, data acquisition boards, and associated software will be referred to throughout the manuscript as the "reference system." A Larson Davis 831 type 1 SLM was also used as a backup reference and to confirm the results on the microphone and watches. Both the LD microphone and SLM were placed in the center of the chamber adjacent to the watches.

A. A-weighted analysis

Eight new watches were exposed to pink noise in the reverberant chamber in 5 dBA increments from 65 to 95 dBA (for seven total noise levels). The measured sound levels were logged by each watch and extracted using the Noise Export app. The measurement from the SLM and the Trident system served as the reference and was considered the gold standard. The mean and standard deviation of the difference between each watch and the reference microphone were calculated, along with the minimum and maximum differences. Simple linear regression was used to determine whether differences among the measurements made by each watch were statistically significant ($p < 0.05$). The difference between the watch measurements and the reference noise levels was assessed graphically with a boxplot.

B. Octave band analysis

The watches were also evaluated based on the accuracy of their measurements to stimuli at 1/1 octave bands (i.e., 125, 250, 500, 1000, 2000, 4000, and 8000 Hz). Noise was generated at 70, 80, and 90 dBA at each of the octave bands. The difference between the watches and the reference microphone was evaluated graphically by constructing a boxplot of the difference in measurements between each watch and the reference microphone for each sound pressure level at each octave band.

III. RESULTS

A. A-weighted analysis

A total of 11 441 measurements were collected through the Noise Export app. Because there is no way to sync sampling times, each watch has a slightly different number of measurements (range: 1427 to 1432 measurements). The average difference between each watch and the reference microphone is presented in Table I. Due to the desynchronization of the measurement intervals, Table I presents results for the entire dataset and the first 95th percentile of the differences in the dataset. On average, the watches measured 3.4 and 2.1 dBA lower than the reference system for the entire dataset and the first 95th percentile of the dataset. The standard deviation of the difference of measurements was much higher for the entire dataset than for the first 95th percentile of the dataset. As indicated by the much larger max difference in the entire dataset compared to the first 95th percentage of the dataset, a small percentage of measurements were collected out of sync resulting in this large difference. This is also seen in Fig. 1 which illustrates the estimated mean and corresponding 95% confidence interval of the difference in noise level between each watch and the reference measurement. The overlapping confidence intervals indicate that the difference in measurements between each watch and the reference system were not significantly different between each watch.

TABLE I. Difference between the reference system and each watch (dB).

Device	N	Min	Mean	SD	Max
Entire dataset					
A1	1427	−2.8	3.2	6.7	59.7
A2	1430	−3.4	3.1	8.2	64.4
A3	1432	−3.1	3.3	7.8	63.4
A4	1431	−2.7	3.9	8.2	64.3
A5	1432	−3.0	3.2	7.2	59.2
A6	1429	−3.1	3.4	8.1	64.3
A7	1432	−2.6	3.6	7.0	59.0
A8	1428	−3.0	3.4	8.0	64.2
Total	**11 441**	**−3.4**	**3.4**	**7.7**	**64.4**
95th percentile of data					
A1	1366	−2.8	2.2	0.2	2.4
A2	1373	−3.4	1.7	0.4	1.9
A3	1376	−3.1	2.0	0.5	2.2
A4	1292	−2.7	2.4	0.5	2.6
A5	1366	−3.0	2.0	0.3	2.2
A6	1335	−3.1	2.0	0.5	2.2
A7	1372	−2.6	2.4	0.3	2.7
A8	1236	−3.0	2.1	0.5	2.2
Total	**10 857**	**−3.4**	**2.1**	**0.5**	**2.6**

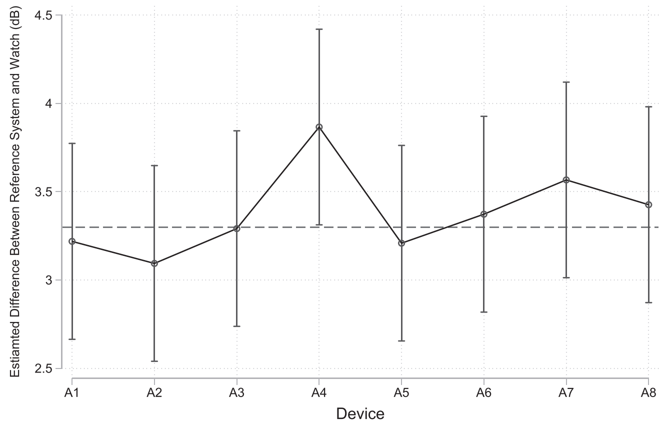

FIG. 1. Mean and 95% confidence intervals of the difference (dB) in measurements between the reference system and watches.

Similarly, there was not a significant difference in measurements between the reference system and the watches across the seven noise levels (Fig. 2). The mean difference between the reference system and the watches was the highest at the 80 dBA noise level (5.8 dB) and the lowest at the 95 dBA sound level (2.5 dB). Figure 2 also demonstrates how a small number of highly influential points are resulting in the large standard deviation and max differences described in Table I. Notably, the watches appeared to sample more frequently when sound levels reached 85 dBA.

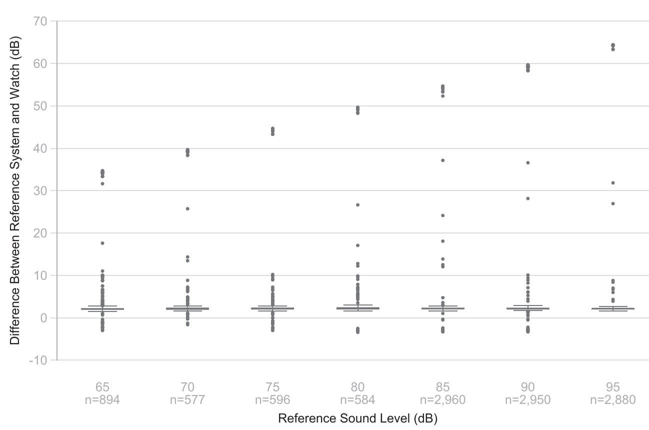

FIG. 2. Difference (dB) in measurements between the reference system and watches across the seven tested noise levels.

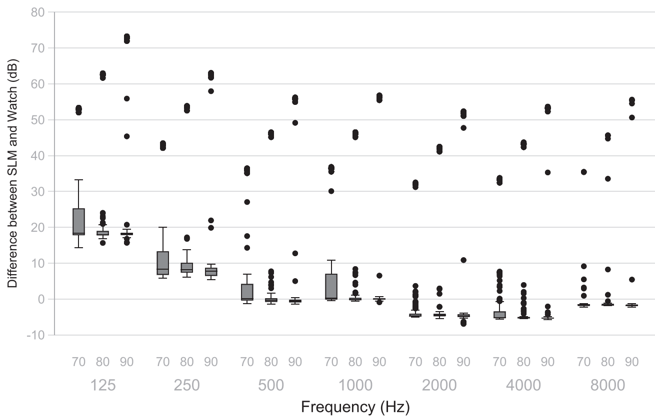

FIG. 3. Distribution of differences (dB) in measurements between the reference system and watches.

B. Octave band analysis

A total of 18 449 octave band measurements were collected. In Fig. 3, the boxes represent the 25th to 75th percentile of the difference [i.e., the interquartile range (IQR)], while the line in the box represents the 50th percentile (median). The boxplot whiskers represent all data points within 1.5 IQR of the nearest quartile. Individual markers outside the range of the whiskers represent statistical outliers from the distribution. All the watches measured lower than the reference microphone from the 125-Hz to 1000 Hz octave bands, with the agreement between the watches and reference steadily improving up to the 2000 Hz octave band, where the watches and reference microphone had the best agreement. At the 4000 Hz octave band, the watches measured higher sound pressure levels than the reference microphone, but when evaluated at the 8000 Hz octave band, the watches again measured lower than the reference microphone.

IV. DISCUSSION

This study appears to be the first published independent evaluation of a wearable consumer noise measurement device (the Apple Watch and associated Noise app). The results of the laboratory evaluation indicated that, on average, the watches measured 3.4 dBA lower than the reference system when exposed to pink noise. However, when only the first 95th percent of the data were considered, this average difference was decreased to 2.1 dBA. The comparison between the entire dataset and the first 95th percent of the data were done to reduce the desynchronization issues inherent in the study procedure. However, the comparison between the two datasets also indicates that even if there are instances where the watch may not fully measure sound levels (such as when initially going from a quiet to a loud environment), the impact on 8- or 24-h averages would likely be minimal.

Although the watches measured outside the 2.0 dBA tolerance stipulated by ANSI for type 2 instruments (ANSI, 2014), the measurements were consistently lower than the reference system. Further, as seen in Fig. 2, the difference between the watches and the reference system are consistent, which suggests that microphone saturation does not occur, at least at levels below 95 dBA. At sound levels at or greater than 85 dBA (i.e., levels that can cause hearing loss with extended exposure durations), the watches appeared to sample more frequently. Sound levels greater than 95 dBA were not tested in this experiment; however, a qualitative examination of the noise application, using music played through a Bluetooth speaker, indicated that the watch will measure sound levels to at least 115 dBA, but further studies will have to be conducted to evaluate the accuracy of measurement made above 95 dBA.

The octave band analysis showed that the watches consistently measured lower sound pressure levels in the frequency bands less than 1000 Hz when compared to the reference microphone. The watches had the best agreement at the 2000 Hz frequency and overestimated sound pressure levels at the 4000 Hz frequency. This could be due to bandwidth restrictions associated with the sampling rate in the watches compared to dosimeters and sound level meters; power limitations in wearable devices are likely to necessitate reduced sampling rates. It could also be due to the influence of the microphone port design on the watch, which may result in directionality-induced impacts on measured sound levels at specific frequencies.

Results from this laboratory evaluation indicated that watches provided more accurate A-weighted measurements in a laboratory setting compared to uncalibrated smartphone apps. In 2014, Kardous and Shaw found that the mean difference between ten different apps available on iOS or Android and a type 1 SLM exposed to pink noise ranged between −13.2 dBA and 3.6 dBA (Kardous and Shaw, 2014). Subsequent evaluations similarly found that only one of the five iOS apps that were tested was within 5.0 dB of a calibrated sound level meter (Nast *et al.*, 2014). A much larger study of seven apps across iOS and Android found that only one iOS app was within 1.0 dB of a reference microphone (Murphy and King, 2016; Nast *et al.*, 2014). Researchers have found that using a calibrated external microphone significantly increased the accuracy of measurements made by smartphone apps (Celestina *et al.*, 2018; Roberts *et al.*, 2016). However, the construction of wearables makes it unlikely that a similar approach could be used for these devices.

Further laboratory studies should be conducted to assess the impact of the microphone location relative to a point source of noise and the impact on the measurement accuracy of clothing or other materials that cover the microphone. Byrne and Reeves (2008) found that in a diffuse sound field of pink noise, the A-weighted errors associated with microphone placement on the left and right shoulders, left and right chest, hanging on the left and right side of the head, and on the left and right earmuffs ranged between −1.0 and 2.1 dBA. To our knowledge, no studies have evaluated the measurement error introduced by a microphone being placed on the wrist, which could introduce a positive or negative bias depending on the location of sound source. This placement introduces the possibility of infinite microphone incident angles in relation to the source; potential contact with clothing, gloves, fingers, and surfaces; potential attenuation when the wrist and watch are located inside a pocket; and other factors that warrant additional evaluation.

In addition, future studies should compare 8-h and 24-h average noise levels as measured by the wearables to those measured by a traditional dosimeter in a variety of occupational and non-occupational settings. Such studies could (1) evaluate the validity of the watch measurements in real-world conditions, including in those settings where noise levels exceed 95 dBA, and (2) increase our understanding of how end-user habits can impact the measurement accuracy of these devices, which will be critical for validating this class of devices for use in large epidemiological studies. Finally, and most importantly, different brands of wearables will need to be assessed as they become available to ensure these devices can be reliably used.

A. Implementation and uses of wearable noise monitors

Occupational and general-purpose sound level measurements are conducted using type 1 (accuracy ± 1 dBA) or type 2 (accuracy ± 2 dBA) sound measurement instruments that must meet the requirements of American National Standards Institute (ANSI) S1.4–1983 (R2007), Specifications for Sound Level Meters (ANSI, 2014). ANSI S1.4 states "…the expected total allowable error for a sound level meter measuring steady broadband noise in a reverberant sound field is approximately ± 1.5 dB for a type 1 instrument and ± 2.3 dB for a type 2 instrument." For compliance with occupational and environmental noise requirements, standards and regulations in the United States require that instruments meet ANSI type 2 specifications. The Occupational Safety and Health Administration (OSHA) noise standard [29 CFR 1910.95] considers type 2 instruments to have an accuracy of ± 2 dBA (OSHA, 2022). The results of this study and the aforementioned uncertainties around the placement of the microphones make it unlikely that these devices, or wearables in general, will be accepted as substitutes for traditional type 1 and type 2 sound level meters and dosimeters in the foreseeable future. Further limiting the use of the devices is the inability for these devices to be calibrated to ensure that the microphone or other components have been damaged.

However, wearable devices and apps, such as those tested here, will greatly increase the number of noise measurements that are collected in the workplace, particularly for workers who lack access to health and safety professionals and appropriate measurement equipment. The accuracy of the wearable devices tested does not meet the relevant standards, and thus these devices do not replace traditional noise dosimeters. However, they are accurate enough to provide valuable insight that allows for a better understanding of exposures and evaluation of the necessity of protective actions. Because an employee wears this device both at work and away from work, these devices can be used by employers implementing Total Worker Health® (TWH) programs (Tamers *et al.*, 2019; Punnett *et al.*, 2020). The watch can alert the user when a certain sound level has been exceeded, allowing the worker to take protective action.

It should be noted that the use of Apple Watches, or other similar devices capable of noise measurements, can help workers and people better understand their exposure to noise in the workplace and general environment. Further, the ease of use and built-in connectivity of these devices could make it easier for community-based participatory research (CBPR) to collect reliable noise exposure data and help drive policy changes for under-represented individuals and communities (Minkler, 2010). However, there are two major concerns with using these devices. The first is that the impact of these devices being used by untrained individuals in the general environment as opposed to the laboratory. The second is that care will have to be taken to ensure that the chosen device does not inadvertently limit a study population by introducing a cost barrier. Further, while users are able to opt-out of software and firmware updates, it is possible that future updates may make the measurements made by watches more or less accurate. While this present study focused on Apple Watches, which have the largest market share for wearables, from a CBPR perspective, it would be ideal if low-cost wearables with broad technological compatibility across operating systems were available (Statista, 2020a, 2020b).

Despite these shortcomings, wearables have value in providing a relatively inexpensive and easy-to-use device capable of capturing exposure data on a scale and at a speed that previously would have been prohibitively expensive. For wearables with access to a cellular network or paired with a phone with cellular access, temporal and geospatial data can be combined with the measured sound levels and provide additional insights into factors affecting exposure. While the potential issues identified in this study should not be ignored, the ability for researchers to collect thousands or millions of noise measurements over an extended period and across a large geographic area is preferable to using a limited number of measurements over a shorter period, which has typically been the case in longitudinal studies (Lambert *et al.*, 2013).

Finally, public health researchers have become increasingly interested in using "big data" (which is commonly defined by its volume, variety, velocity, and value, to improve health outcomes) (Hu *et al.*, 2014; NAS, 2018). It is estimated that in 2020, there will be approximately 600×10^6 connected wearable devices, with over one billion devices expected to be in use in 2022 (Statista, 2020b). Although the majority of these devices will be used in developed countries, tens of millions of wearables are expected to be used in countries that have limited access to occupational and environmental health professionals. Even if only a small fraction of these devices are used for exposure assessment purposes, the volume of data that will be generated will be immense and useful to researchers.

V. CONCLUSIONS

This is the first study to evaluate the accuracy of the Apple Watch in a laboratory setting and according to standard testing procedures. The results indicate that the Apple Watch is generally accurate enough to provide reliable noise measurements but are less accurate in quieter (and inherently less-risky) environments. Additionally, there are still issues around how the behavior of a user may contaminate any measurements collected by the wearables. However, this approach can be used as a template for future studies of similar devices. While wearable consumer devices will not replace traditional noise dosimeters for compliance measurements, they are valuable tools (particularly when more expensive, dedicated sound measurement equipment is not available), and their ease of use makes these devices useful for longitudinal studies of noise exposure and TWH programs. We anticipate that devices like this will be used to generate a vast amount of exposure data that can be easily correlated with a time and location and that these extremely large datasets will develop and employ new "big data" analysis approaches to better characterize human exposures to noise and associated health risks.

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[1]See supplementary material at https://www.scitation.org/doi/suppl/10.1121/10.0012916 for an image of the test chamber setup.

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