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Wearable sensors for multifactorial personal exposure measurements – A ranking study

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ABSTRACT

Individuals are simultaneously exposed to multiple environmental stressors during their daily life. Studies of adverse health effects and their etiology as well as recommendations for a healthier life style demand for an assessment of multifactorial personal exposure, according to the exposome concept. A challenge is to record exposure while people are moving in heterogeneous urban environments. Therefore wearable sensor technologies are becoming a promising way to measure personal exposure continuously: indoors, outdoors and even on the move. So far, studies which test the accuracy and usability of wearable sensors for multiple stressors are lacking. Performance evaluations are important and should take place beforehand, especially to ensure the success of citizens-oriented studies. For the first time we rigorously examined the accuracy and application suitability of wearable sensors for acoustic noise, heat (temp), particle number counts (PNC) and geo-location (GPS) in different environments. We present an extensive device inter-comparison and a ranking of the sensors based on performance measures, Taylor diagrams, Bland-Altman plots, and ease-of-use aspects. The sensors showed moderate to high correlations with precision reference devices (r = 0.4–0.99). Differences between errors outdoors and indoors suggest that environmental conditions have impact upon the accuracy of the sensors. Reaction time, recording interval, and sensor ventilation are features that play a crucial role for both ease-of-use and accuracy. We conclude with a final performance ($\mathcal{P}$) ranking: $\mathcal{P}$ (GPS) > $\mathcal{P}$ (noise) > $\mathcal{P}$ (temp) > $\mathcal{P}$ (PNC). The results are relevant for future epidemiological studies of multifactorial exposure of individuals and their health and should guide the selection of wearables when persons are involved that are technically untaught. Inferences from multifactorial data are based on the performance of all sensors and the weakest chain links are PNC and temp sensors for which our article recommends urgent improvements.

1. Introduction

Cities are prone to significant levels of multifactorial environmental stressors that are a product of population growth and its consequences such as intensified human activities like traffic, surface sealing and urban densification. Moreover, these environmental stressors are modified by climate change (Mueller et al., 2017). Consequently, citizens are exposed to a mixture of environmental stressors. Many epidemiological studies have provided evidence of adverse health effects related to urban air pollution, acoustic noise and heat stress (Babisch et al., 2007; Mueller et al., 2017; Muzet, 2007; World Health Organization, 2005). Following the concept of exposome (Nieuwenhuijsen et al., 2014; Wild, 2012), multi-pollutant influences on an individual's health status are receiving more attention (Billionnet et al., 2012; Juarez et al., 2014; Tonne et al., 2017; Vlachokostas et al., 2012). Human exposure assessments are currently dominated by the use of data from expensive and fixed measurement stations that is analyzed with modeling techniques like interpolation, land-use regression or dispersion models. This data is helpful for conclusions related to public health, but has strong limitations assessing individuals exposure (Kumar et al., 2015; Snyder et al., 2013; Steinle et al., 2015b). It cannot be used to capture the dynamic personal exposure to environmental stressors at short temporal and spatial scales as it refers only to pollution in a certain radius ignoring the individuals' daily mobility (Dias and Tchepel, 2014; Kwan, 2009; Northcross et al., 2013).

Therefore, techniques to gather information about local and person-based concentrations of environmental stressors are gaining importance (Dons et al., 2017; Huck et al., 2017; Park and Kwan, 2017; Steinle et al., 2013). The use of wearable sensors to collect personal exposure data has attracted the interest of a broad range of environmental researchers as well as authorities and local communities (Jovasevic-Stojanovic et al., 2015; Khoury and Ioannidis, 2014). Recent technical

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developments provide new opportunities to use wearable sensors that record real-time contaminations at small-scales. Despite the advantages of wearable devices compared to static devices, the data accuracy is a major issue that has to be assessed before the utilization in applied research projects (Aguiar et al., 2015; Jerrett et al., 2017; Lewis and Edwards, 2016). Moreover wearable sensors are more often part of personal exposure assessments that involve citizens. Accordingly devices that are easy to use can improve wearing compliance, operators satisfaction and the overall success of the exposure study with citizens (Lawless et al., 2012).

Some recent studies have already tested single wearable sensors. However, studies testing a combination of sensors for multifactorial environmental stressors are sparse and omit the focus of application by the general public (Borrego et al., 2016; Castell et al., 2017; Manikonda et al., 2016; Nyhan et al., 2016). Therefore, the purpose of this study is to make a rigorous comparison of different wearable sensors for temperature, noise, particle number concentration (PNC) and geo-position (GPS), with the aim of providing a ranking of sensor performance and ease-of-use. The ease-of-use rating is based on technical features and handling of the sensors (Loh et al., 2017). The comparison of the sensors is based on a 60 s recording interval as the PNC test device is fixed to this setting. All ratings are summarized in a sensor ranking.

2. Materials and methods

For our experimental setup we have chosen test sensors that weight up to 500 g, can be worn and operated by laypeople in personal exposure studies (Table 1, Fig. SI-2). The devices can be attached to the body (arm, belt, and/or pants pocket), bags or backpacks. All test sensors operate continuously with an internal battery for at least 6 h. The test sensors were selected based on recent publications and the aforementioned criteria (Amaral et al., 2015; Gozzi et al., 2016; Manikonda et al., 2016; Steinle et al., 2015a). Furthermore, we selected mobile devices from environmental technology companies that we considered to be state-of-the-art devices at the present time and use them in our study as reference devices.[1] We note that in our definition the reference has a higher accuracy (stated by the manufacturer) compared to the test devices and is calibrated (Table 1). In addition, we tested GPS devices as GPS is often used to register the locations of environmental parameters measured by wearable sensor devices. GPS accuracy is also a crucial part of personal exposure studies to make sense of the environmental measurements in the spatial context. Considering that in the urban space the GPS signal can be disturbed due to street canyons, building density and green spaces, we compared the GPS devices between different urban structure types (USTs) in the City of Leipzig, Germany (Fig. SI-1).

We tested sensors for the following environmental parameters (Table 1): particle number counts (1 reference, 1 test device), acoustic noise (1 reference, 1 test device) and ambient temperature (1 reference, 2 test devices). For geo-positioning we tested 3 GPS devices, in this case the reference was the original route. The data of each parameter group was paired and synchronized by the timestamp. The devices' internal clocks were synced before the tests.

2.1. Sensor specifications

2.1.1. Particle number concentration

Particle number concentration (PNC) was measured using optical light scattering with optical particle counters (OPC) (Koehler and Peters, 2015). These OPCs utilize a light source (laser diode), to illuminate a selected sample of air that has mechanically controlled constant flow produced by a fan (TSI, 2013). When flowing through the air channel of the device, a photodetector measures the light that is scattered off by reflection, refraction and diffraction. On the basis of the intensity of the flash, particles are counted and sized at the same time. For the measurements of PNC we used OPC devices configured to count particles of an aerodynamic diameter $> 2.5\,\mu m$ and $> 0.5\,\mu m$, namely the Dylos DC 1700 as test device (Dylos Cooperation, Riverside, California, USA) and a TSI AeroTrak 9303 (TSI GmbH, Aachen, Germany) as the more accurate and calibrated reference device (Table 1). The recording interval of the Dylos is fixed to 60 s (recording the mean value of the last 60 s).

2.1.2. Acoustic noise

Acoustic noise is a generally unwanted or unpleasant sound and experienced very subjectively. Here, we refer to its intensity (loudness) measured as sound pressure level. The human perception of sound depends on its frequency and we applied the A-weighted filter to adjust measurements to the human hearing. Operationally, noise pollution is often not continuously measured, but modelled for noise maps, as stated in Art. 47c Federal Immission Control Act (Germany, 2017). In our experimental settings we tested a smartphone based application using the internal microphone signal to register A-weighted sound levels (Kardous and Shaw, 2014). For the evaluation of noise level accuracy of the smartphone we compared an iPhone 5S running the application "dbMeter" (Schosoft, Munich) with the precision sound level meter PCE-322A (PCE GmbH, Meschede, Germany), both working with condenser microphones. The recording interval was 60 s.

2.1.3. Temperature

Ambient air temperature is measured continuously at meteorological stations. Additionally, temperature stations operated by the general public (crowdsourced) create a spatio-temporally dense fixed network (Meier et al., 2017). Temperature measurements on the move are still scarce and mostly realted to short-term projects. For person-based temperature measurements we used a Pt-1000 as well as sensitive semiconductors reducing their resistance with temperature increasing over a relatively small range (negative temperature coefficient, NTC). The test devices we evaluated were a TI Sensor Tag (Texas Instruments, Dallas, Texas, USA) and the TSI Q-Trak 7565 (TSI GmbH, Aachen, Germany). As a reference we chose a calibrated Testo Testostor 171–6 (Testo SE & Co. KGaA, Lenzkirch, Germany) with active ventilation and high accuracy (Table 1). The recording interval was set to 60 s.

2.1.4. Global positioning systems

Current global positioning system (GPS) devices use different gauging techniques, and we tested:

(1) A smartphone (iPhone 5s) with the application MyTracks (Dirk Stichling, www.mytracks4mac.info, Germany) that combines classic GPS, assisted GPS (aGPS) based on cell coverage and wireless local area networks (WLAN) in the near surroundings of the smartphone user. (2) A small monofunctional GPS sensor Qstarz BT-Q1300ST (Qstarz International Co. Ltd., Taipei, Taiwan) using classic GPS. (3) A Garmin 60CSx (Garmin GmbH, Garching, Germany) with classic GPS and barometer. All classic GPS devices use the EGNOS-System (European Geostationary Navigation Overlay Service) to calculate the position using corrected satellite signals. Sampling rate was set to 5 s. In contrast to temperature, noise and PNC, which we compared to a precision reference instrument, the GPS devices have been evaluated against the original route. These original way points were plotted on a map based on a geo-referenced (WGS84) digital orthophoto (DOP) in ArcGIS Desktop (Version 10.4). After the tour all recordings were imported in ArcGIS as point features and, for each point, the nearest distance to the original route was calculated from the UTM coordinates (in m) using Analysis Tool "Near". Distances were considered positive (negative) when the point was right (left) hand from the original track.

[1] The term reference device must not be confused with "reference measurements of an air pollutant" defined by official authorities as the European Commission.