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An open-science crowdsourcing approach for producing community noise maps using smartphones

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ABSTRACT

An alternative method is proposed for the assessment of the noise environment, on the basis of a crowdsourcing approach. For this purpose, a smartphone application and a spatial data infrastructure have been specifically developed in order to collect physical data (noise indicators, GPS positions, etc.) and perceptual data (pleasantness), without territorial limits, of the sound environment. As the project is developed within an Open Science framework, all source codes, methodologies, tools and raw data are freely available, and if necessary, can be duplicated for any specific use. In particular, the collected data can be used by the scientific community, cities, associations, or any institution, which would like to develop new tools for the evaluation and representation of sound environments. In this paper, all the methodological and technical issues are detailed, and a first analysis of the collected data is proposed.

1. Introduction

Environmental noise pollution has an impact, not only on humans [1] but also on most animal species that inhabit the territories [2,3]. The noise assessment and the reduction of its impact is therefore an important issue, widely supported by national regulations in many countries. In Europe, for example, the European Directive 2002/49/EC requires that cities with more than 100,000 inhabitants produce noise maps, thus, define action plans to limit noise annoyance, but also communicate to citizens about the quality of their sound environment [4].

Classically, noise maps are generally produced by modelling based on sound sources and acoustic propagation models, using standard methods like the CNOSSOS-EU [5] or the ISO 9613-2 [6], for example. While such approaches provide an overview of the environmental noise, they remain very limited for several reasons: the noise sources taken into account are limited to transport sources; noise emission models are very simplified (for example, urban road traffic is considered constant on a road section, without taking into account traffic dynamics [7]; propagation models are based on approximations (for example, taking into account the micro-meteorological effects considered in the standard methods is not *a priori* relevant in urban environments [8]); obtaining noise maps requires important calculation times at the scale of an agglomeration; the input data of the models are often incomplete (for example, the ground type is chosen arbitrarily due to a lack of information) and, even if numerous data are now made accessible in the form of open data, their use as input data is far from being straightforward [9,10]. All these limitations result in a lack of realism of the regulatory noise maps. Moreover, the question of the evaluation of the perception of the environmental noise by users is still raised since such standard noise maps do not integrate this component.

The other approach that is allowed by the European directive is based on noise measurements. However, given the considerable number of measurement points required at the agglomeration scale, this solution is often rejected from the outset. However, today, with the growing number of smartphone users and considering the continuous improvement of the metrological quality of smartphones, it becomes possible to envisage the realization of an extremely dense noise observation network, spatially and temporally. This approach thus makes it possible to produce more realistic noise maps, integrating all the involved sound sources, as well as their temporal dynamics, without other limitations than those related to metrological issues and measurement protocol.

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Thus, several initiatives have emerged in the last 10 years and have shown the relevance of the approach [11], despite the *a priori* lower quality of acoustic measurements [12,13]. In addition, the participatory aspect of such an approach potentially allows citizens/users to get feedback on their own sound environment and to contribute to a citizen and scientific approach. For the time being, however, these approaches are still quite experimental and few have actually led to fully operational systems, and, much less, in an 'Open science' framework. Indeed, the principles of the accessibility, the sustainability, the quality, as well as the temporal and spatial representativities of the collected data are of major concern in such approach, in the greatest transparency towards contributors and users.

The proposed method is fully in line with these principles, by considering the Open science concept at the very heart of the method. Thus, the method is entirely based on the development and use of Open source components, as well as the free availability of all data produced (*i.e.* Open data), while ensuring the greatest transparency, regardless of the public that is involved. In addition, the proposed approach is part of a systemic approach to control the data chain, from collection to mapping, which required the implementation of a specific Spatial Data Infrastructure (SDI). The method for collecting the noise data in the environment and the spatial data infrastructure are detailed in Sections 2 and 3. In Section 4, the collected data are described, and, as a preliminary study, the full raw database is analyzed. The long-term supply of the database is also discussed.

2. Collecting data from smartphones

2.1. General principle

The main goal of the approach is to collect noise data and other relevant information, ideally at any location in the environment and at any time. All the data produced by each contributor participates in the feeding of a community database, which should enable a detailed representation of the sound environment in space and over time. To collect data, the contributor uses a specific smartphone application (Section 2.2). All data are then transmitted to a remote server that is in charge of their post-processing, archiving and sharing (Section 3).

In practice, the contributor:

1. starts a measurement with his smartphone;
2. moves along a free path;
3. stops the measurement after a certain time;
4. then, if desired, completes the measurement with some additional information;
5. and uploads data to the remote server in order to feed the community database.

2.2. Smartphone application

A specific smartphone application, called NoiseCapture, has been developed to perform acoustic measurements synchronized with the moving of a contributor in space (*i.e.* a geo-referenced measurement).

The NoiseCapture application offers several features:

- The 'Measurement' view (Fig. 1(a)–(c)) takes the form of a sonometer-like display and presents the usual sound level indicators (A-weighted equivalent sound levels: 'fast', minimum (Min), maximum (Max), average (Mean)). The measurement time and GPS accuracy are also specified. Using the same view, on different tabs, the real-time sound spectrum (Fig. 1(a)) and spectrogram (Fig. 1(b)) on the frequency range [100 Hz, 16 kHz], as well as the real-time traveled path on a map (Fig. 1(c)), can be displayed;
- Once the measurement is completed, the contributor accesses a 'Description' view (Fig. 1(d)), which allows him to supply additional information (a descriptive text and photographs), as well as an evaluation of his own perception of the sound environment. Thus, the contributor provides feedback about the pleasantness of the sound environment, with 5 levels [14,15] and a list of 'tags' corresponding to the presence of noise sources and to the measurement conditions [16,17] This information is optional, but may eventually enrich the physical noise indicators and help to qualify the data;
- The following 'Results' view (Fig. 1(e)) summarizes the acoustic indicators: equivalent sound levels over 1 s ($L_{\mathrm{Aeq,1s}}$), distribution of $L_{\mathrm{Aeq,1s}}$ over the measurement time, minimum and maximum values of $L_{\mathrm{Aeq,1s}}$, percentile indicators L_{A10}, L_{A50} and L_{A90}, and average sound spectrum over the duration;
- Finally, the sound levels along the user paths can be viewed on a map (Fig. 1(f)), superimposed with community data.

For the need of the present study, the application has been developed for Android Operating System (OS) based smartphones only to limit development costs while benefiting from a large panel of contributors. Indeed, although acoustic measurement with iOS devices are of better quality [18], mainly due to the lower variability of smartphone models running this operating system, Android smartphones still represent more than 80% of the market in 2016, compared to approximately 15% for iOS [19].

2.3. Measuring noise with the smartphone

2.3.1. Metrological considerations

Several studies have focused on the metrological quality of smartphones for acoustic measurement using internal microphone [20,21]. The low quality of the measurement can be indeed an obstacle to the use of smartphones for the evaluation of the environmental noise, to which is added the impact of the measurement protocol and of the operator (*i.e.* the citizen). While a smartphone may indeed be considered far from the characteristics of a Class 1 sound level meter (according to the IEC 61672-1 [22]), particularly in terms of linearity in level, background noise, directivity, etc., recent works have shown that the current characteristics of smartphones could be compatible with the features required for an assessment of the sound environment [23–25].

Using an external microphone instead of the smartphone's internal microphone can also greatly improve acoustic measurements [26]. In addition to better directivity and sensitivity, the use of a windscreen with the microphone may sometimes be necessary in outdoor environments. It should also be noted that the smartphone's acoustic calibration can be simplified if the external microphone is of a size compatible with a conventional acoustic calibrator.

The question of measurement dynamics may arise, since the Android specifications only guarantee optimal acoustic measurement for sound levels between 72 and 102 dB. While most smartphones go beyond these specifications, a problem can arise for the lowest sound levels characteristic of, for example, quiet urban areas, and sometimes for very high levels. However, it is difficult to specify these "low" and "high" level limits precisely, since they vary greatly from one smartphone to another [25].

While people must be aware of the metrological limitations of smartphones for acoustic measurements, it is to be hoped that, as part of the proposed approach, some metrological biases can be reduced because of a very large number of measurements, performed by different people, with different smartphones. In addition, the continuous improvement of the hardware quality of smartphones [18] must be also considered. Indeed, on the one hand, users are becoming more and more demanding in terms of quality and functionality, and on the other hand, manufacturers and OS specifications are becoming more and more restrictive. For example, considering the Android OS, since version 4.3, smartphone manufacturers must comply with more stringent audio recording specifications, in order to ensure compatibility with future versions of the OS [27].

Fig. 1. Screenshots of the NoiseCapture application: (top) 'Measurement' views in (a) 'Spectrum', (b) 'Spectrogram' and (c) 'Map' modes; (bottom) (d) 'Description', (e) 'Results' and (f) 'Map' views.

2.3.2. Signal processing

Within the application, the calculation of acoustic indicators is based on the following methodology:

1. the analysis of a continuous audio signal (*i.e.* the sound environment);
2. a real-time signal processing for the calculation of equivalent sound level indicators ('Measurement' view of the application);
3. a post-processing of statistical indicators from $L_{\mathrm{Aeq,1s}}$ ('Results' view).

In NoiseCapture, Audio analysis is performed using the native Android AudioRecord API. The VOICE_RECOGNITION mode is used to disable the gain and noise reduction filters that can be applied by the OS. The process collecting sound samples is attached with a special priority, named THREAD_PRIORITY_URGENT_AUDIO, to ensure no loss of sound samples in case of high Central Processing Unit (CPU) processing load.

The acoustics indicators are calculated on samples of 125 ms, which allows a high resolution display of a spectrogram. The sound spectrum is obtained by applying a Fast Fourier Transform on the time signal, after a 125 ms Hann windowing with a 2/3 overlap, then calculating the energy per third-octave bands. The same procedure is also considered for the calculation of the sound spectrum over the total duration of the recording. The A-weighting is applied to the time signal in accordance with standard IEC 61672-1 [22]. Statistical indicators are then evaluated using conventional methods.

The use of a time filtering for the third-octave band analysis, as recommended by the standard IEC 61672, currently requires too many resources to be implemented in most of smartphones, particularly for a real-time display. However, one can quite imagine that in the near future, this type of processing will be possible on smartphones, even for entry-level ones.

2.3.3. Smartphone calibration

The Android specifications for the VOICE_RECOGNITION mode set the audio recording sensitivity such as that a 90 dB sound power level (SPL) source at 1000 Hz yields Root Mean Square (RMS) value of 2500 for 16-bit samples. Consequently, a robust signal processing implementation in a 'perfect' smartphone should verify this specification and gives correct sound level values. However, most of time, a smartphone indicates a wrong value, *i.e.* different from the value that is expected. One possible reason is that some smartphone manufacturers do not fully meet the Android requirements, which could explain also why while using the same noise measurement application different values are given between different smartphone models.

It is therefore necessary to correct the measured value in order to obtain correct absolute noise levels. In NoiseCapture, as in other analogous applications of this type, a calibration procedure is proposed from a 'reference' device, in global level or for a given frequency band. If an external microphone is used having a diameter compatible with a calibrator (or $\frac{1}{2}$ inch type), its calibration is strongly recommended. Otherwise, the value measured with a given smartphone must be compared with the one obtained under the same measurement conditions with a reference measurement system, *i.e.* an already calibrated sound level meter or smartphone. In all cases, for a relevant correction, it is important that the reference noise level is chosen within the optimum sound level range for acoustic measurement, between 72 and 102 dB, as defined by the Android specifications.

2.3.4. Measurement protocol

In addition to metrological quality, the realization of the measurement by the contributor is also an essential condition for building a high quality noise database. It is obviously impossible to be 'behind' each contributor to check whether the measurement was carried out in good conditions. However, it is possible to make some recommendations, such as: carrying the smartphone in one hand (not in the pocket), not hiding the microphone, making a measurement without adding an 'artificial' noise, using an external microphone, or calibrating the smartphone. Compliance with these recommendations could be verified, *a posteriori*, by studying data from other phone sensors as suggested by Rana et al. [28]. However, in the proposed approach, the idea is to limit the collection of data from the smartphone's sensors and to reduce the size of the database that is produced. Thus, in order to limit the bias due to incorrect measurement protocol, the approach preferentially focuses on 'Experts' as contributors (see Section 4.2).

2.4. Geolocation and timestamping of the measurement

An accurate location of measurements is essential to obtain quality noise maps, as long as the spatial fluctuations of noise can be significant and since the receiver can be closed to the sound source. Within the NoiseCapture application, the geolocation is preferably achieved by the Global Positioning System (GPS). If there is no GPS location (for example inside buildings), the WIFI or GSM location can take over, but is characterized by an accuracy better than 15 m or 1500 m respectively, which is not acceptable. According to the Android specifications, the estimated accuracy of the GPS value is defined so that there is 68% chance that the 'true' location is within a circle defined by a radius equal to the precision value (in meters).

In addition to the geolocation, the exact date and time of the location, as well as an estimate of the location accuracy, are recorded. It is important to note that the time provided by the GPS may be slightly different from the acoustic measurement one because the two clocks are not synchronized.

3. Spatial data infrastructure

3.1. Principle

The proposed approach required the development of a Spatial Data Infrastructure (SDI) that is specific to the problem of the sound environment, in order to connect, store, catalog and disseminate the data obtained by the application. Indeed, a SDI provides capabilities to achieve these tasks using web services. As pointed out in Ref. [29], using a SDI for noise mapping strategies:

- permits to encode data in a similar manner, thus achieving semantic interoperability between models;
- offers a natural way to expose data on the web and to report information following common web services specifications;
- helps to share common noise methodologies by reinforcing the accessibility of harmonised and publicly shared data sets.

It is therefore in this context that the SDI, called OnoMap (contraction of 'Open noise Map'), was developed. This SDI can also be used for other applications requiring environmental data processing. In the context of harmonization, standardization and interoperability, such infrastructure may prove particularly interesting as underlined in Ref. [29] for applying the European INSPIRE and 2002/49/EC directives [4,30].

This central component in the project was developed on the basis of common languages and standards, notably following Open Geospatial Consortium (OGC[1]) recommendations. The OnoMap SDI is based on five Open source applications (Fig. 2), deployed on a remote server to which data are transferred from the NoiseCapture application [32]:

- A spatial relational database, using the couple 'PostGreSQL/PostGIS' and allowing to store, organize and process the data;
- A map server 'GeoServer', used to display data (stored in the database) through standardized streams such as WMS (Web Map Service) and WFS (Web Feature Service);
- A web-mapping library, based on the 'LeafLet' component, allowing the creation of interactive maps that can be consulted on a web page in order to view and query noise data;
- Processing tools, based on the 'H2GIS' component (geospatial functions library) and the 'OrbisGIS' software [33], used to describe and execute online processing on the data, in compliance with the Web Processing Service (WPS) standard.

3.2. Data produced by the smartphones

The data transferred by the contributor to the remote server take the form of a ZIP archive, containing 3 files [31]: a 'README.html' file describing the two data files 'meta.properties' (Table 1) and 'track.geojson' (Table 2). The first data file, in a text format, contains general information about the smartphone and the application, as well as the L_{Aeq} values over the recording time. The second file, in '.geojson' format (a popular geospatial data interchange format based on JSON encoding[2] and dedicated to vector data), contains information related to the measurement, for each of the measurement points (each point is defined by its latitude and longitude coordinates in World Geodetic System 1984 (WGS 84) format).

3.3. Data generated by the SDI

Following the principles of the Open Science approach, the free availability of data collected by the community of contributors is essential, which is also fully in line with the current Open Data policies led by national and European authorities, such as the Etalab project[3] in France or the INSPIRE Directive in Europe [30]. It ensures that the produced data can be reused by any audience for the possible development of new 'services' for the citizen, and particularity in our case, a possible reuse for new contributions by the scientific community involved in the assessment of noise.

All raw data produced by contributors data are grouped in a ZIP archive, organized by country, then by administrative division within each country. For each administrative division (subsequently noted [country_adminintrative_division] in the filename), data are then located into three GeoJSON files, each corresponding to a specific geometry (Fig. 3): a measurement path, a measurement point in a path and

[1] http://www.opengeospatial.org/.
[2] http://geojson.org/.
[3] https://www.etalab.gouv.fr/en/.

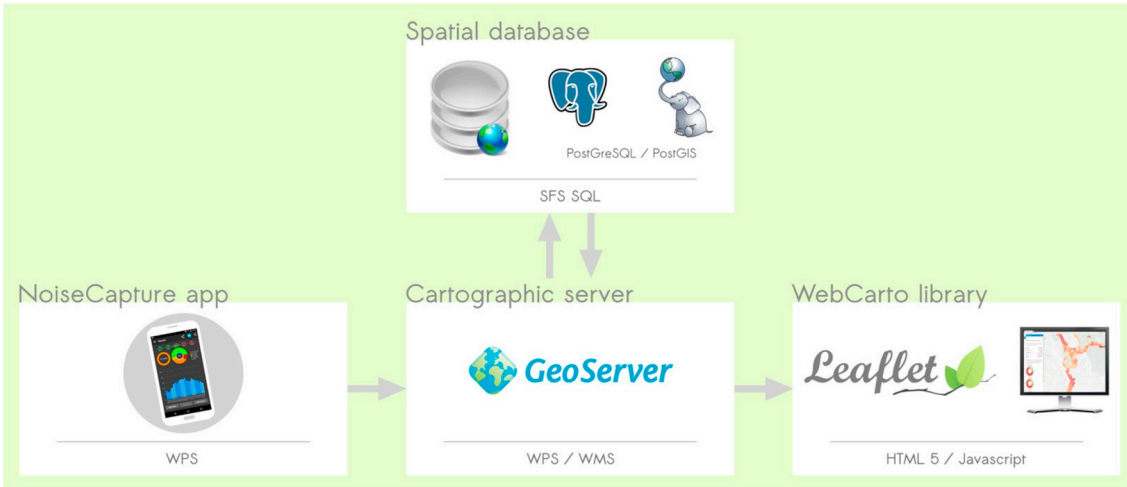


Fig. 2. Principle of the Spatial Data Infrastructure 'OnoMap' developed for NoiseCapture. From Ref. [31].

Table 1
Description of the 'meta.properties' file transferred by the application to the remote server.

Properties	Format/Type/Unit	Description
version_name	String of characters	NoiseCapture version
version_number	Integer	Version number
build_date	UTC date (epoch UTS)	Date of build (The 'epoch' format defines the initial date from which time is measured. It is given using the Coordinated Universal Time (UTC) format.)
record_utc	UTC date (epoch UTS)	Recording date and time (ms)
uuid	String of characters	Universal Unique Identifier (UUID)UUI, defined at each installation of the application
device_product	String of characters	Smartphone reference
device_model	String of characters	Smartphone model
device_manufacturer	String of characters	Smartphone manufacturer
time_length	Integer	Recording duration (in s)
gain_calibration	Real value	Correction after calibration (in dB)
tags	String of characters	List of tags, separate by a comma
pleasantness	Integer	Pleasantness value between 0 and 100 (but only 5 value are available from the application (0, 25, 50, 75, 100), which correspond to 5 possible evaluation of pleasantness from unpleasant to pleasant)
leq_mean	Real value	L_{Aeq} value on the whole recording duration (in dB(A))
user_profile	String of characters	Contributor profile: 'NONE', 'NOVICE', 'EXPERT'. This is the user's assessment of his level of expertise in the field of acoustic measurement.

Table 2
Description of the 'track.geojson' file transferred by the application to the remote server. The properties are associated with each of the measurement points (every second) in the same recording (*i.e.* the same path). In the absence of GPS location, some data (marked with the symbol*) are not filled in.

Properties	Format/Type/Unit	Description
geometry	Point	Coordinates (latitude, longitude and elevation*) of a measurement point
leq_mean	Real value	L_{Aeq} value on the whole recording duration
accuracy	Real value	GPS value accuracy (in m)
location_utc	UTC date (epoch UTS)	Date of the last geolocation
leq_utc	UTC date (epoch UTS)	Date of the measurement
leq_id	Integer	Unique identifier of the measurement

an aggregation area:

- '[country_administrative_division].tracks.geojson': information relative to a contributor measurement path (*i.e.* a measurement) (*cf.* Table 3);
- '[country_administrative_division].points.geojson': information relative to each measurement point of a same measurement path (*i.e.* one measurement point every second) (*cf.* Table 4);
- '[country_administrative_division].areas.geojson': a basic aggregation of all measurements of the contributors community in urban areas (*cf.* Table 5).

All the collected data with a location accuracy less than 15 m, can be display on a world map,[4] with different levels of aggregation (according to the scale factor, Fig. 4). On lower scales (scales 1 to 14), an aggregation of the data by hexagon (number of measurement points), can be visualized (see for example Fig. 4(a) and (b), at scale 3 and 12 respectively).

For greater scales (for example Fig. 4(c)), the representation shows a noise map obtained from the collected noise data in each hexagon. General statistics (number of measurements, temporal profile of the

[4] http://noise-planet.org/map_noisecapture/index.html.

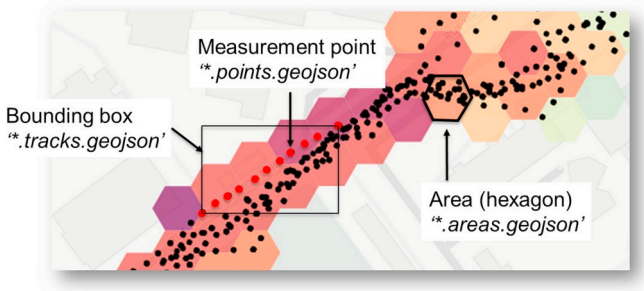


Fig. 3. Correspondence between data and GeoJSON files/objects. Symbol * refers to the country and the administrative division '[country_administrative_division]'.

sound level, contributing countries, distribution of tags …) are also available for information (see Fig. 5).

As of July 23, 2018, since the official launch of the application in August 29, 2017 (version 1.0.0, release 28), more than 24,000 contributors have produced around 85,500 measurements paths (or tracks) which represents 17.5 millions of 1 s measurements (measurement points) and is equivalent to 203 days of a continuous measurement. Data come from 146 countries, but mainly from United states and France with 38% and 31% of the measurement points respectively. All raw data produced by contributors are fully available from the project website[5] under ODbL License [31].

4. Discussion on collected data

4.1. Privacy policy

In this approach, respect for the user's privacy is essential:

- The application does not make any audio recordings; only classical acoustic indicators are calculated, based on real time signal processing;
- No personal information (telephone number, IMEI smartphone code, user name, email, …) is collected. Only one identifier (UUID, see Table 1) that is created at the installation of the application, is uploaded to the remote server which allows to associate several sets of measurements to the same application installation. This identifier, which cannot be associated to a given user, would make it possible *a posteriori*, for example, to apply a specific treatment on the same sets of measurements (as a post-calibration);
- The description text and the pictures that the contributor can associate with a given measurement in the 'Description' view are only stored on the smartphone and are not uploaded to the remote server;
- The contributor has a full control of the measurement: the contributor triggers the measurement himself (there is no background measurement) and may voluntarily decide to not contribute to the data collection.

4.2. Contributor profile

One of the approach's challenges lies in the possibility to produce a very large amount of data. This therefore requires the widest possible dissemination of the application and its intensive use. As in many participative projects, the question of the contributor's motivation, beyond an initial enthusiasm (thus over the long term), is crucial for the process [34]. If a financial motivation is excluded (the contributor would be paid to carry out measures), which however should not be consistent with the principle of a participative approach, the contributor must therefore find a personal interest in using the application, or adhere to the general interest that such a project can produce. In the present case, the NoiseCapture application is voluntary developed as a handheld sound level meter, in a way that people could also use the application for their own use, independently of the project objectives (*i.e.* people are 'Users', but not necessarily 'Contributors').

Another issue is based on the quality of the collected data (see Section 4.4). It would indeed be counterproductive to federate a large community of contributors that collects data of poor quality, even unusable. In the present approach, the target audience is primarily 'experts', made up of people with a 'given technicality and expertise' in the field of environmental measurement, and who would be interested either professionally (acousticians, technicians in technical services, community workers, students and teachers in the environmental field, etc.) or personally (environmental association, etc.) in noise measurement for the production of community noise maps. Note that the property 'user_profile' of the 'meta.properties' file (*cf.* Table 1) is a way to obtain information on the contributor profile. At this stage of experimentation (Fig. 6), around 10.3% and 31.9% of contributors have declared themselves as 'Expert' and 'Novice', respectively, against 47.5% without any expertise (unset for 10.3% of the contributors).

To extend the contributor community and their expertise, the approach promotes the realization of a special event, called 'NoiseCapture Party'. This event, which is under the responsibility of an 'Ambassador' (*i.e.* a person with a given experience in noise measurement, *i.e.* an 'Expert'), aims at training users and at organizing measurement sessions in specific areas. The problem of finding a large number of contributors is therefore reduced to a more restricted search for ambassadors, who would train new ambassadors. By targeting this community of experts, it ensures also a better initial measurement quality, through a collective calibration of smartphones and the respect of a measurement protocol. Of course, this approach does not prevent a person from contributing to the project individually; each contribution has its own value, for the acoustic data as well as for the information it can provide on the use of the application. At the moment, the data produced in such 'NoiseCapture Party' represent only 0.3% of the total number of measurement points, but it could be increased in the future.

4.3. Contributor behavior

4.3.1. App (un-)installs

Regarding the evolution of the number of users/contributors, Fig. 7 shows the daily installs and un-installs of the Android application on a device (data from Google Play Console), compared to the new contributors to the database each day. At first, the first two peaks (at the end of August and at the beginning of September) are due to the launch of the application and the enthusiasm it generated through the information relayed by the media. Over the considering period, the total number of installs (acquisition of new users) and un-installs are 50627 and 37591 respectively, leading to a number of 'active' installs of 13036. On these remaining installs, about 9663 installations have been really active in the last 30 days (*i.e.* 19% of the first installs).

In details, Fig. 8(a) shows the installer retention rate by month. As example, an installer-to-30 days retention rate of 62% (August 2017) means that 62% of users are still using the application 30 days after the first installation. One can observe that, even if the number of first installs is decreasing in the last months (as already observed at Fig. 7), the installer-to-30 days retention rate tends to stabilize around 32% (note that more data are needed to establish long-term statistics). Comparing the number of new contributors to the number of installs, it shows that not all users contribute to the data collection for the database: the ratio contributors/users is around 47% over the whole considered period.

Fig. 8(b) shows that the behavior that is observed for the NoiseCapture App, is quite similar to those observed for most Android Apps. This figure is based on statistics from 125 millions of Android devices and applications with more than 10 000 installation worldwide (Google

[5] http://data.noise-planet.org/index.html.

Table 3
Description of the '[country_administrative_division].tracks.geojson' file.

Properties	Format/Type/Unit	Description
the_geom	Polygon	Bounding box of the measurement path (polygon object with 5 points)
time_ISO8601	UTC date (ISO 8601)	Starting date of the measurement path
time_epoch	UTC date (epoch UTS)	Starting date of the measurement path
pk_track	Positive integer	Measurement identifier (link to file '[country_administrative_division].points.geojson')
track_uuid	String of characters	UUID of the measurement path
gain_calibration	Real value	Correction after calibration (in dB)
noise_level	Real value	L_{Aeq} value on the whole recording duration (in dB(A))
tags	String of characters	List of tags, separate by a comma
pleasantness	Integer	Pleasantness value between 0 and 100
user_profile	String of characters	Contributor profile

Table 4
Description of the '[country_administrative_division].points.geojson' file.

Properties	Format/Type/Unit	Description
the_geom	Point	GPS coordinates of the measurement point
time_ISO8601	UTC date (ISO 8601)	Date of the measurement point
time_epoch	UTC date (epoch UTS)	Date of the measurement point
time_gps_ISO8601	UTC date (ISO 8601)	UTC date of the last GPS localization
time_gps_epoch	UTC date (epoch UTS)	UTC date of the last GPS localization
pk_track	Positive integer	Measurement identifier (link to file '[country_administrative_division].tracks.geojson')
track_uuid	String of characters	UUID of the measurement path
noise_level	Real value	$L_{\mathrm{Aeq,1s}}$ value on the measurement point (in dB(A))
speed	Real value	Estimation of the speed at the measurement point (in m/s)
orientation	Real value	Horizontal orientation of the smartphone (in ∘)
accuracy	Real value	GPS localization accuracy (in m)

Apps are excluded) collected on the first 5 months of year 2015 [35]. Even if NoiseCapture statistics are incomplete (Google Play Console does not give 60 and 90-days retention rates), the observed behavior is very closed to those observed for the 'best' Android Apps (note that reference [35] does not clearly specify the criterion on which the applications in question are ranked, although we may think it's in terms of number of downloads).

In practice, a majority of contributors used the application only once (48.9%) or twice (20.8%) (Fig. 9), before un-installing it. We can think that people downloaded the application to test it, and then uninstalled it, due to lack of interest. Only a few people contribute intensively to data collection. The top 100 of contributors (who each collected between 60 and 600 measurements), alone represents nearly 16% of the total number of measurements. As shown by Fig. 6, the distribution of contributor profiles in the top 100 is quite the same that for the whole amount of data. This analysis shows very clearly the interest of concentrating on a limited number of contributors, but who are very active and seem to adhere to the approach. Ideally, these users should be relied upon to act as 'Ambassadors' and if possible 'Experts', and hosts of NoiseCapture Parties.

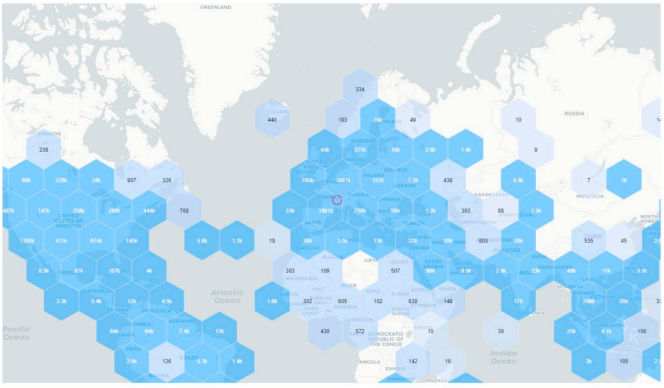
4.3.2. Collected data

One interesting information is the nature of data collected by contributors. Considering the measurement duration (Fig. 10(a), 65.9% of the measurement tracks have a duration less than 60 s (with a major contribution between 10 and 20 s). At the opposite, the top 1000 of the contributions with the greater duration is between 51 min and 8 h, which means that contributors make efforts to make long-term measurements. However, a part of these contributors (76.2%) may remain in the same position (Fig. 10(b)), *i.e.* without moving in their environment. Anyway, these two types of behavior are complementary, since having a long measurement at the same place allows to have a precise description of the temporal noise dynamics, while having a long journey allows to give more information on the spatial distribution of noise.

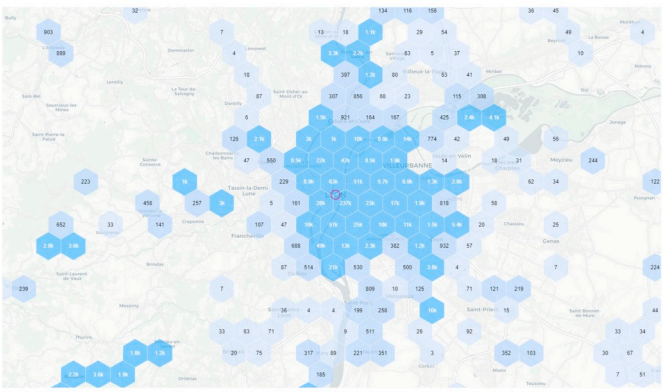
As already mentioned in the previous paragraph, around 69.5% of contributors have realized only one or two measurements (Fig. 9). They clearly represent the part of the users that install and test the

Table 5
Description of the '[country_administrative_division].areas.geojson' file.

Properties	Format/Type/Unit	Description
the_geom	Polygon	'Bounding box' of the area of aggregation (hexagon)
cell_q	Integer	Hexagon position in the grid (EPSG:3857 WGS84 Web Mercator)
cell_r	Integer	Hexagon position in the grid (EPSG:3857 WGS84 Web Mercator)
LA50	Real value	L_{A50} of the aggregation area (in dBA)
laeq	Real value	$L_{\mathrm{A,eq}}$ of the aggregation area (in dBA)
laeq_profile	Real value	24 h distribution of sound level for a week day, a saturday and a sunday
mean_pleasantness	Real value	Mean value of the pleasantness (value between 0 and 100)
measurement_count	Integer	Number of measurement points (*i.e.* measurement duration in s, in the aggregation area)
first_measurement_ISO_8601	Date UTC (ISO 8601)	Date of the first measurement point
first_measurement_epoch	Date UTC (epoch)	Date of the first measurement point
last_measurement_ISO_8601	Date UTC (ISO 8601)	Date of the last measurement point
last_measurement_epoch	Date UTC (epoch)	Date of the last measurement point



(a) Scale 3



(b) Scale 12

(c) Scale 16

Fig. 4. Map representation of the collected data at several scale. For lower scale factor, only the number of measurement points by hexagon are given (scale factors from 1 to 14). For larger scale factors, noise maps are represented from the noise data that are aggregated in each hexagon.

application, and next, un-install it quickly. In our approach, what is of major interest is the part of the contributors that regularly realize new measurements. One can observe that 6.6% of the contributors have performed more that 9 measurements, and between 60 and 600 measurements for the top 100 of the best contributors.

Another point of interest is the behavior of the contributors to feed the information concerning their own perception of the noise environment: 46% of the contributors do not select any tag (Fig. 11(a)), while 43% select 1 to 3 tags. The analyze of the tags distribution; for the measurements that contain at least one tag (54% of the measurements), for the 'Measurement conditions', show that the 'Indoor' tag is selected for 18% (Fig. 11(b)), meaning that the remaining measurements with tags (82%) correspond to outdoor measurements. Considering the goal of the proposed approach, which consists in producing community noise maps, such result was of course expected. However, considering the amount of data collected in indoor configuration, in the future collected data could be used to obtain additional information of the noise exposure inside buildings. The 'Test' tag represents 8% of the selected tags. Considering the nature of this information, all measurements that mention this tag should be removed, to perform relevant analysis in the future. In addition, measurements realized during rainy and windy conditions (2% and 4% respectively) should be carefully considered. In terms of 'Predominant sources', 'Chatting' (17%), 'Road' (9%) and 'Footsteps' (8%) are the most used tags. Lastly, one can observe that the pleasantness information is present for only 24.4% of the measurements, with a certain balance between the 5 possible values.

4.4. Relevance and limitations of the collected data

Once the community is active, it is the amount and the quality of the collected and post-processed data that will make it possible to obtain relevant information on the sound environment. This opens up original and very interesting research perspectives, as this subject is still little studied. The post-processing to be implemented in the future (see Section 4.5), will have to deal with noise measurements and geolocation that are sometimes of poor quality.

As mentioned before, the smartphone should be calibrated before any measurement. Fig. 12 shows that around 80.9% of the measurement have a correction value of 0 dB, meaning that the calibration process has not been carried out (the case of an exact value of 0 dB after calibration is negligible). When realized (9.1% of the measurements), the correction value is mainly between −5 and 5 dB, but non-negligible amount of data shows a correction greater than 20 dB, which is questionable either regarding the quality of realization of the calibration protocol, or concerning the metrological quality of the smartphone. Conversely, and even if the number of measurements performed as part of a NoiseCapture Party is low at the moment (0.4% of the whole measurements), the ratio of NoiseCapture Party measurements that include a calibration process is close to 78.8%, which, here again, confirms the interest of organizing such measurements events. In addition, looking at Fig. 6, one can observe that NoiseCapture Parties count a few more 'Novice' and 'Expert' contributors (49%) than for the all amount of data (42%).

Even if the noise measurements are performed in an optimal configuration, a bad location of the measuring points can completely annihilate the interest of the whole measurement. For example, Fig. 13(a) shows that the accuracy on the location of the measurement is sometimes very insufficient, greater than 15 m for 24.4% of the measurements, which can result from measurements performed indoor or in narrow streets, or when geolocation is obtained using the WIFI or phone network in the absence of GPS geolocation. A lack of GPS location quality can make it difficult to analyze a track on which outliers appear (Fig. 14). In this situation the use of GIS layers like OpenStreetMap can be an asset to tag the location of the measurement. These data can also be used to filter out inaccurate measurements (*i.e.* in a building or in a tunnel).

In addition, on the basis of a limit speed of 5 km/h for a pedestrian in an urban environment, it is nearly 37.9% of the data that should be excluded (Fig. 13(b)), since the measurements must have been made in a moving vehicle, such as road transportation, but also by boat, train or airplane (speed greater than 5 km/h for 7.5% of the measurements) or because of the absence of GPS geolocation (empty values 'null' for 30.4% of the measurements). Considering both a geolocation accuracy less than 15 m and a speed limit of 5 km/h, 53.4% of the measurement points should be discarded. Considering NoiseCapture Party measurements only, this ratio drops to 27.0%.

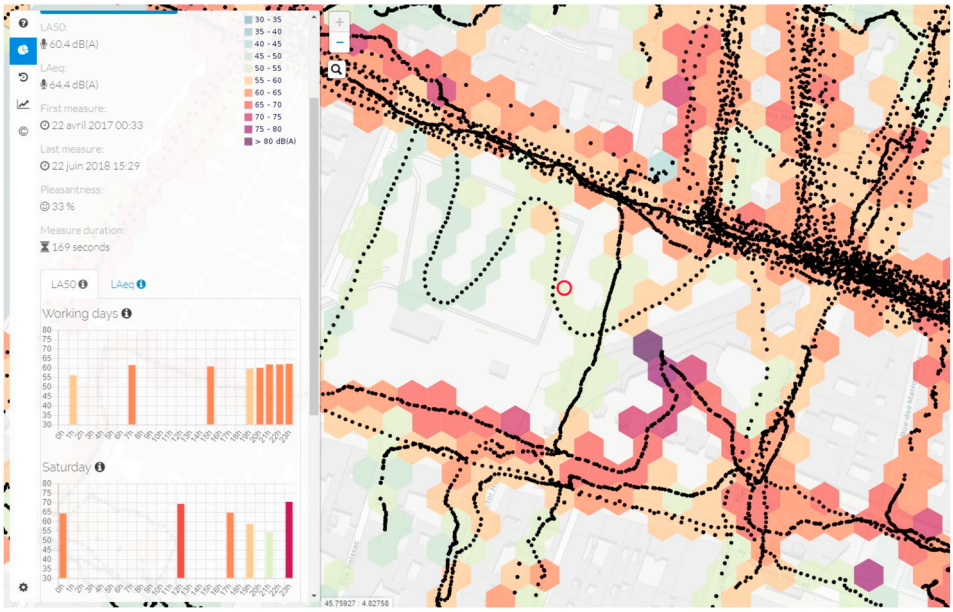


Fig. 5. By selecting an hexagon (from scale factor 16), additional information are given. The location of each measurement point is also available by selecting the corresponding layer. Measurements carried out in the City Center of Lyon (France).

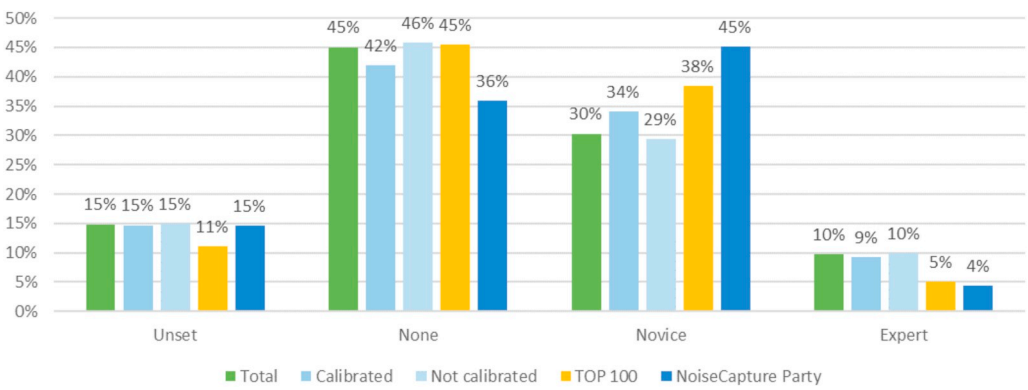


Fig. 6. Contributors profile on all collected data, on the calibrated data, uncalibrated data and for the top 100 of contributors).

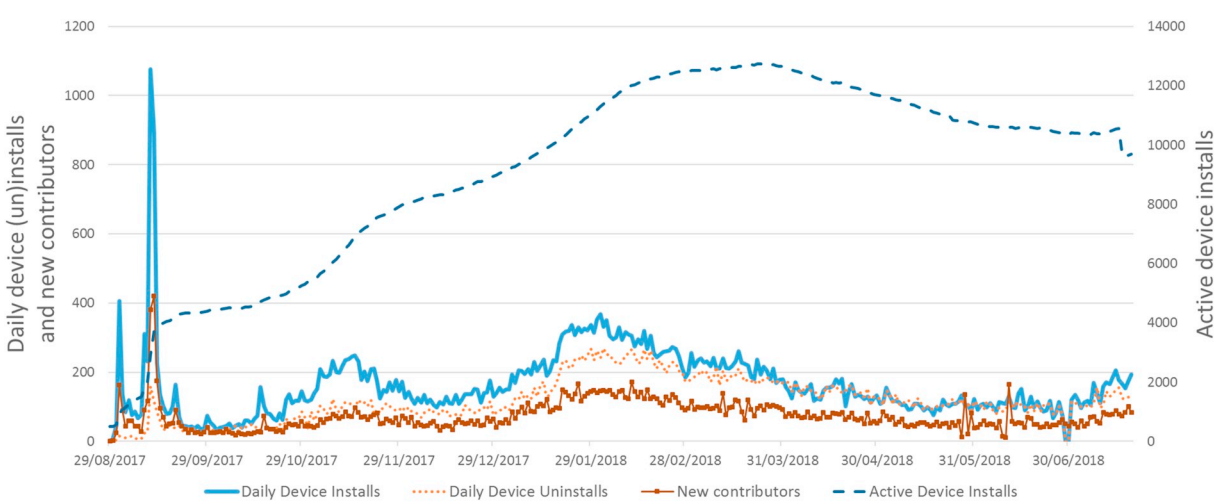
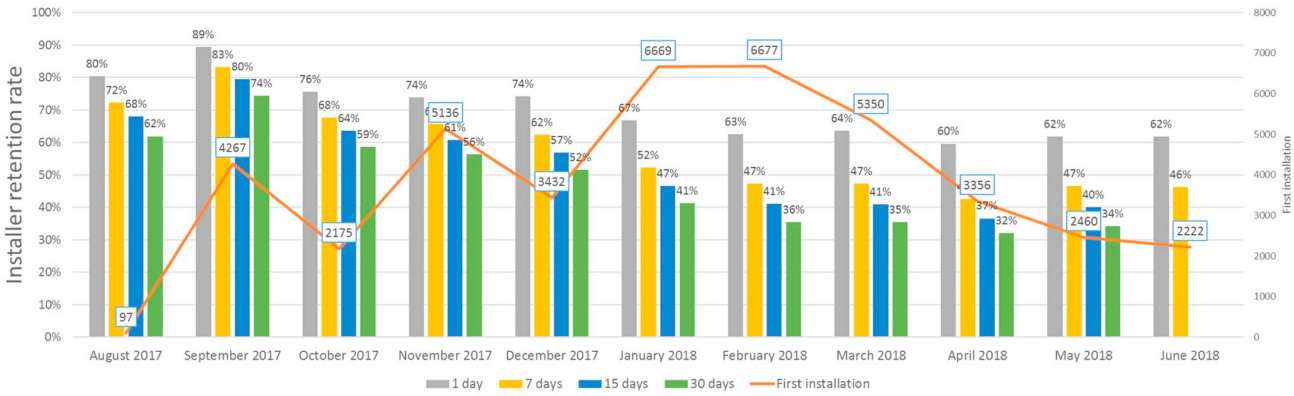
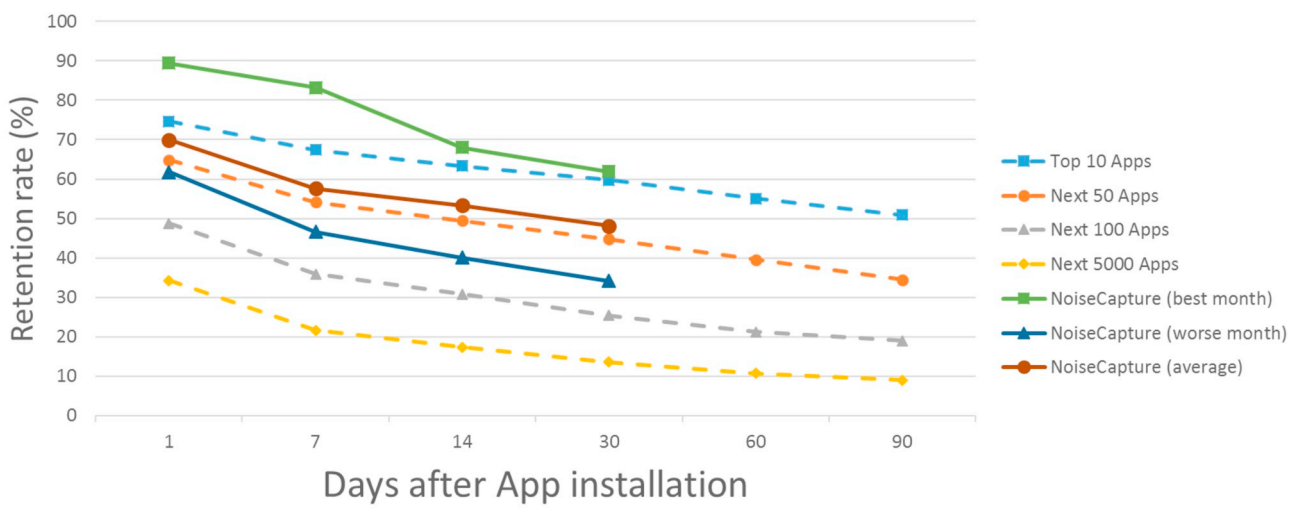


Fig. 7. Daily (un-)installs and total number of active devices (*i.e.* the App has been used in the last 30 days) since the launch of the NoiseCapture App (data from Google Play Console), compared to the number of contributors (data from NoiseCapture database). The first two peaks (at the end of August and at the beginning of September) are due to the launch of the application and the enthusiasm it generated through the information relayed by the media.



(a)



(b)

Fig. 8. App Retention rates: monthly evolution ((a)) and comparison with other Apps ((b)) (data from Ref. [35] collected from 125 millions of Android devices and applications with more than 10 000 installation worldwide (Google Apps are excluded), on the first 5 months of year 2015).

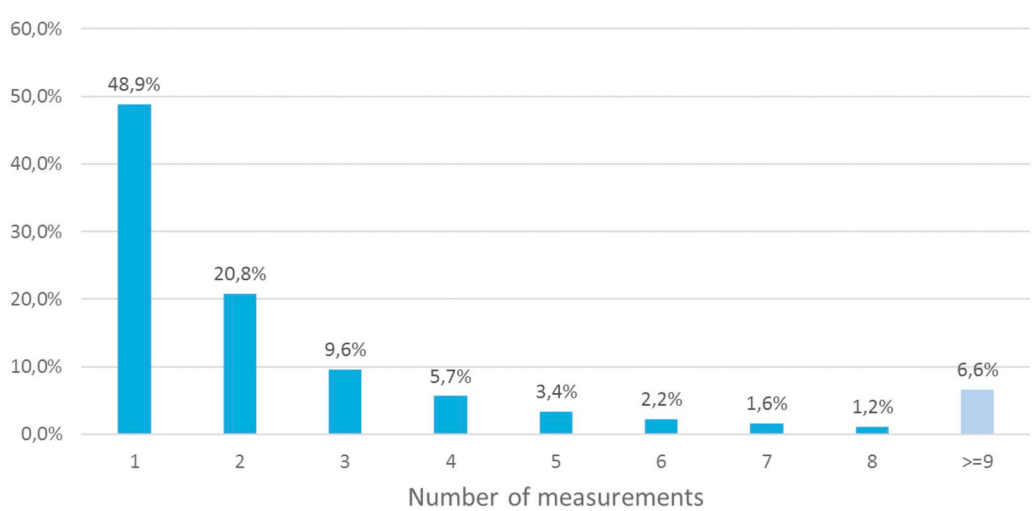


Fig. 9. Distribution of the number of measurements.

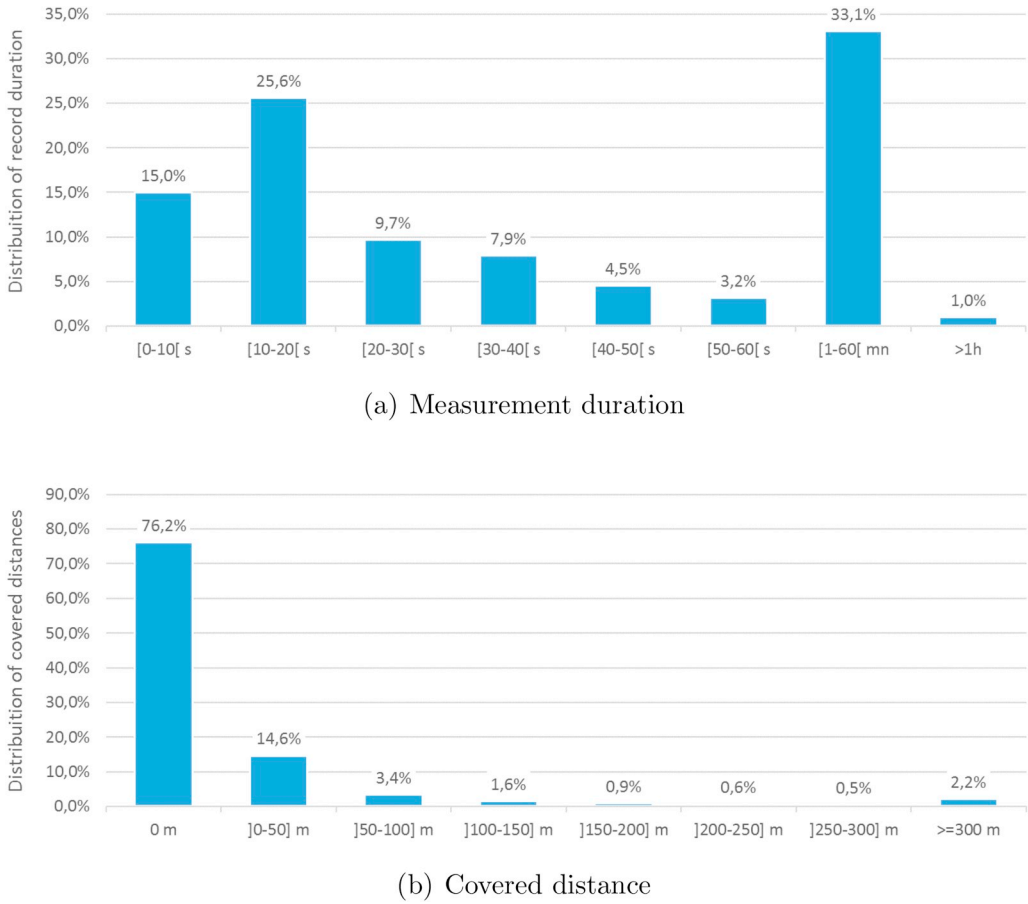


Fig. 10. Measurements statistics: distribution of (b) the measurement duration and of (b) the covered distance.

4.5. Using collected data for environmental noise assessment

Once the database has been qualified, the question turns to the best possible use of the data to assess and improve the sound environment. At this stage, several applications are possible.

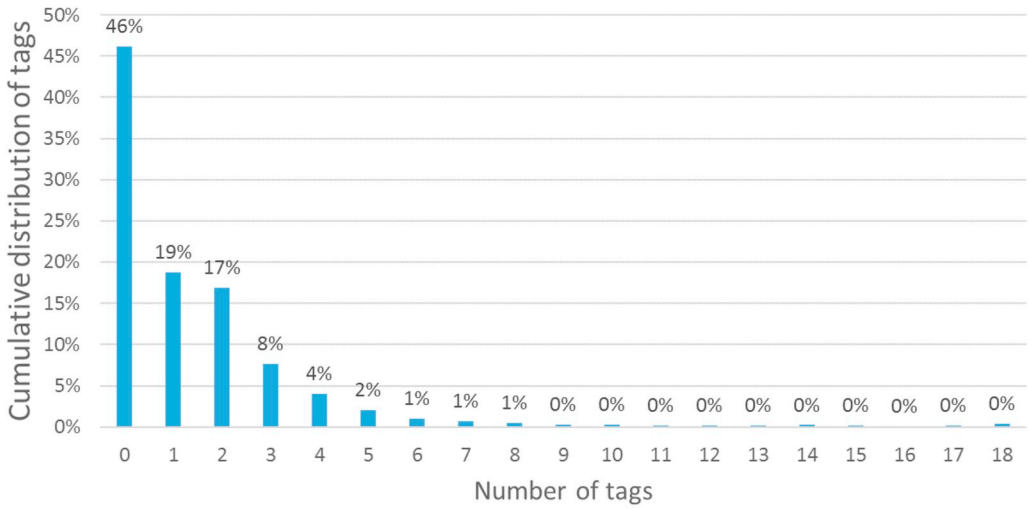
The most direct application is the production of noise maps, including all the sound sources. Since the assessment of noise levels is based on measurements, we can therefore expect a more realistic representation of the sound environment, compared to approaches based solely on modelling. The other advantage of this approach is the possibility of having a temporal description of sound levels, instead of a long-term assessment This will be all the more relevant as the same geographical area will have given rise to measurements at different times of the day, for different weekdays and at different times of the year. This could thus highlight the daily and seasonal nature of a sound environment [36,37]. If the temporal distribution of the measurements is *a priori* insufficient to have a relevant description of the sound environment of a given place over time, the solution may be to use standard temporal profiles to extrapolate the missing data [38]. With the continuous addition of new measurements at a given location (*i.e.* at other times), it is quite possible to envisage a continuous updating of these temporal profiles, which, through a “domino effect”, will make it possible to improve the noise prediction over the entire considered territory.

While the production of a noise map including all noise sources seems to be an important step compared to current possibilities, such noise map does not meet the objectives of the European Directive 2002/42/EC, which aims to produce specific noise maps for transportation noise sources, such as road traffic. Based on the current version of NoiseCapture, the easiest way would be to filter all measurement data with the ”Road” tag. However, a questionable level of representativeness should be expected, since this method is essentially based on the behavior and motivation of the operator for checking the tag. A much more effective solution would be to integrate into the NoiseCapture application, a signal processing algorithm that automatically identifies a certain number of sound sources, based on the measured audio signal, as proposed by Gloaguen et al. [39]. Some NoiseCapture tags could therefore be preselected and possibly validated by the operator. To deal with a potentially insufficient amount of data, an additional solution would be to merge the NoiseCapture measurements with a numerical model as proposed by Ventura et al. [40].

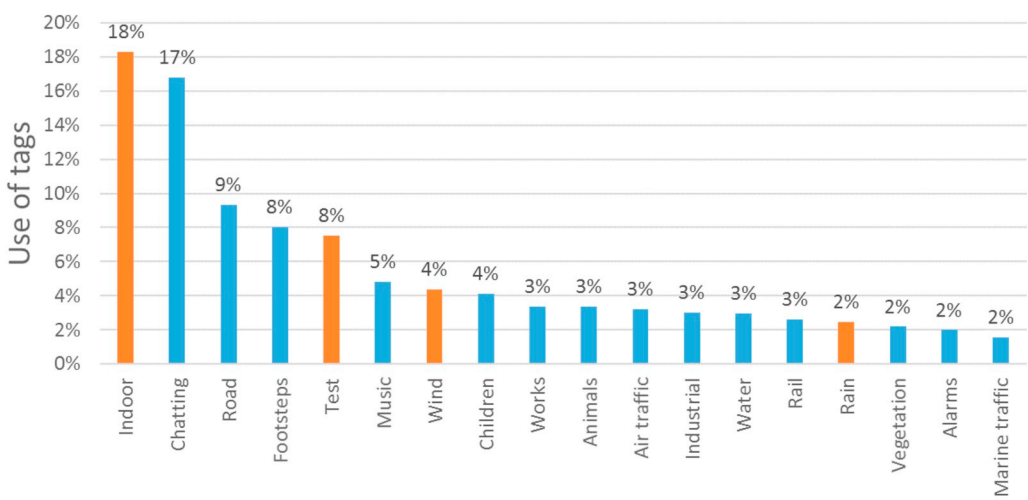
The assessment of the quality of the sound environment cannot be limited to the knowledge of sound level indicators alone. Very recent models now make it possible to assess the quality of the environment on the basis of both physical indicators and knowledge of the presence of sound sources [14,15]. The possibility of using tags and source identification processing, as discussed above, would therefore also make it possible to produce sound maps closer to the perception [41].

As mentioned above, a large number of the data collected are described with the ’Indoor’ tag, which potentially opens the way for the database to be used for large-scale indoor assessment purposes. However, one of the difficulties lies in the ability to properly locate a measurement in a particular building (requires a different location technology than GPS) or to assign a measurement to a building (by crossing geolocated database). Once this problem of location has been eliminated, it would therefore be possible to obtain a noise level estimation inside closed areas, such as public places (restaurants, shopping centres, gaming rooms, etc.).

As discussed above, knowledge of the speed associated with each measurement point makes it possible to exclude measurements that would not correspond to a pedestrian. On the other hand, the data discarded would therefore *a priori* be associated with mechanical modes



(a) Cumulative distribution of tags



(b) Number of measurement tracks with tags

Fig. 11. Tag usage statistics: (a) cumulative distribution of tags and (b) tag selection (red tags: 'Measurement conditions'; blue tags: 'Predominant sources'). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

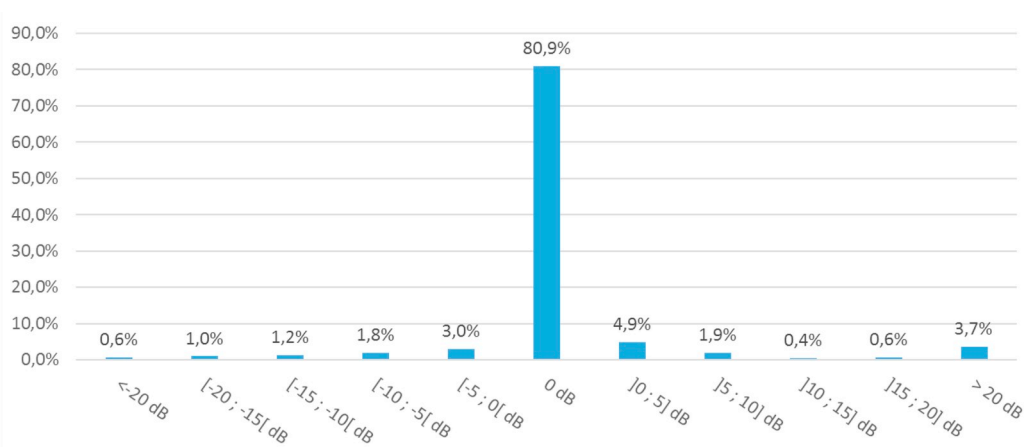


Fig. 12. Distribution of value of the noise level correction after calibration.

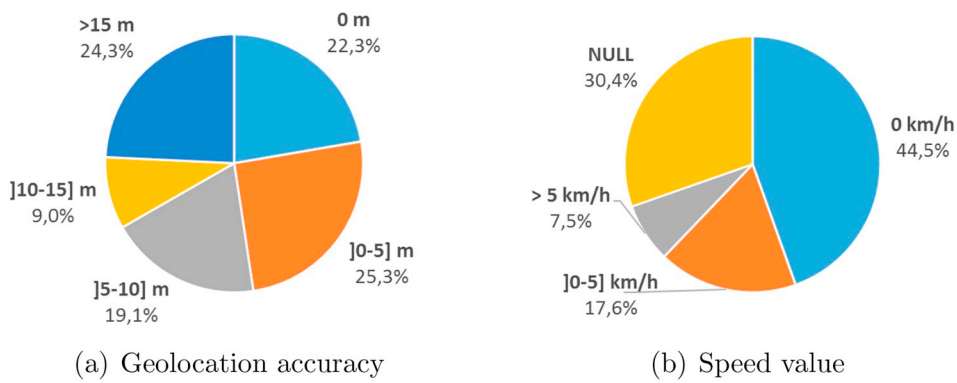


Fig. 13. Geolocation of the measurement: (a) accuracy of the location (m); (b) speed of the measurement point (m/s).

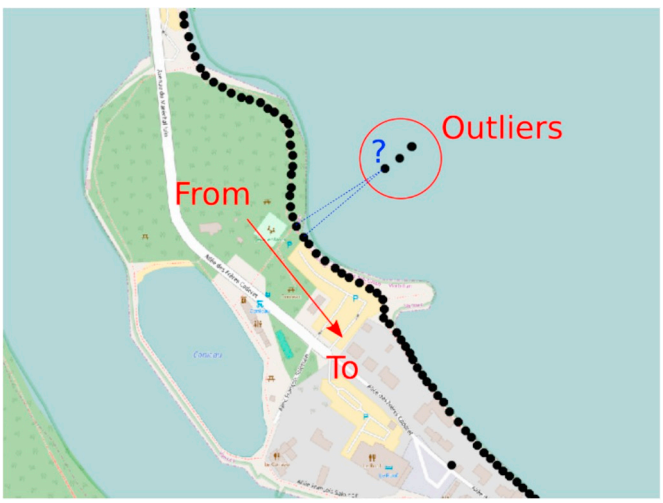


Fig. 14. GPS track with outliers.

of transport (bicycle, motorcycle, bus, tramway, train, etc.). Cross-referencing the GPS position of these measurement points with other geolocated database would make it possible to identify the mode of transport used. Therefore, it is potentially possible to assess noise levels within certain modes of transport, which would therefore complement the assessment of the outdoor sound environment.

The potential applications discussed above, implemented simultaneously, would ultimately provide an assessment of a person's noise exposure over a journey, whether outside or inside a building or means of transport.

5. Conclusion

In this article, we have proposed an alternative method for assessing the sound environment, based on a participatory approach using smartphones. If such experiments have already been proposed, the approach proposed here is, on the one hand, fully operational and, on the other hand, fully integrated into an Open Science philosophy. The technology deployed can thus, if necessary, be adapted to other needs in environmental acoustics, or to other problems requiring data collection *via* a participatory approach.

The smartphone application that has been developed makes it possible to collect both physical sound level data and perceptual data on the sound environment. At the level of the community of contributors, this data collection should eventually make it possible to have a more realistic representation of the sound environment than those obtained conventionally by approaches based on numerical modelling.

However, the quality of this evaluation depends very much on the quality of the data collected, and particularly on the metrological quality of smartphones, both from the acoustic and geolocation points of view, but also on the measurement protocol. Considering the metrological aspects, the permanent and rapid evolution of smartphone capabilities should contribute to the continuous improvement of the database. Recent works have shown, for example, that a smartphone application on iOS, with an external microphone could achieve compliance with most of requirements for Class 2 sonometers [42]. In addition, the implementation of specific protocols for acoustic calibration of smartphones could also be considered. With regard to the measurement protocol aspects, it seems appropriate to focus primarily on contributors with some technical expertise in the field of environmental noise measurement. In particular, the organization of one-off events (NoiseCapture Parties) supervised by specialists ('Ambassadors') should contribute to produce a more relevant database. As example, in France, contacts have already been made with technical services of local authorities and state services to set up a community of experts.

The statistical analysis of the first contributions to the database already provides many lessons. Even if a huge number of installations of the application is observed, many of them are very short in duration (*i.e.* some people install the application, try it and uninstall it immediately). As for many smartphone applications, the retention rate after several weeks decreases gradually, but in the case of NoiseCapture, the behavior is similar to that of the best Android applications, which is very positive. The future effort must therefore focus on the minority of users who contribute very actively to data collection, by carrying out numerous measurements over very long periods and journeys. The level of engagement of this community of active contributors will undoubtedly require the addition of new features to create better interactivity.

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