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Urban Soundscape Informational Quantization: Validation Using a Comparative Approach

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ABSTRACT

Through interaction with environmental parameters such as light or sound, urban and architectural spaces generate ambiances with identifiable characteristics. This notion of ambiances is related to the human being position through its perception of environmental physical phenomenon during a pedestrian walk. Presented work aims to evaluate, so as to characterize, the impact of sound ambiances (soundscape) onto an urban pedestrian pathway using GIS spatial dynamical mapping. To carry out this scheme, our research work within AMBIOFLUX project concerns spatial interaction between sound ambience (soundscape) and man urban spatial trajectory (soundwalk). Spatial impression of soundsources or soundmarks has to be both defined through acoustical measurement and perception informational evaluation. The remainder of this paper is dedicated to the evaluation's methodology of the pedestrian pathway's acoustic fingerprint using the GearScape spatial formalism described thereafter. Preliminary results we have obtained will also be presented and validated.

Keywords: Ambience, Soundscape, Soundmarks, Entropy evaluation, Information dimensioning, GIS semantics

1. Ambient Environment Perception and Representation

AMBIOFLUX project concerns spatial interaction between sound ambience (soundscape) and a human urban spatial trajectory (soundwalk). It defines ambiances as an anthropocentric view of the global environmental production through physical, human and built constraints of architectural and urban design. To model it, we consider urban space as a field of data aimed at ambiances physical parameters description through multi-phenomenal characterization [1].

An application of this principle is currently proceeded through this interdisciplinary research project, called AMBIOFLUX, funded by CNRS, French National Centre for Scientific Research, and MEEDDAT Ministry (French Ministry dedicated to Ecology, Energy, Sustainable Development and land use planning) under PIRVE's contract (*Programme Interdisciplinaire de Recherche Ville et Environnement*). The corresponding research work aims at producing dynamical urban environmental index for spatial interaction indicators between ambience and urban walkthrough [2].

From a software point of view, GearScape (a customi-

zation of the OrbisGIS project initially developed by E. Bocher, F. González Cortés and T. Leduc in the CNRS FR 2488 context [3]) original spatial formalism processing aims to qualify pedestrian spatial interactions with producing a set of ambient dynamical indicators.

This approach is therefore founded upon elementary sound sources description, organization and recognition with proceeding to its elementary hierarchic identification and systemic modeling [4,5].

2. Soundmarks as Soundscape Psychophysical Encoded Elements

Soundscape informational dimensioning will be considered through urban sound sources spatial psychophysical indicators formulation, soundmarks. Murray Schäfer introduces the word "soundmarks" as a derivation of the word "landmark", to identify sounds which sign the outstanding role of sounds to characterize a place [6]. In this sense, soundmarks describe sound events which get a specific informational status, mainly denotative, that means they are strong identity revealers.

The dedicated informational order scaling corresponds to near-order indices, which can be evaluated through maximal information entropy. Therefore, soundmarks are

defined as maximum-entropy sources a soundwalker can meet, defined as the most consciously emerging urban-situated events within his world-line, for a given urban trajectory. They are computed using local entropy sources calculation H [7], as described in equation (2).

2.1. Worldline as a Soundwalk Representation Model

For the pedestrian who wanders around the urban space, the ambient phenomenon overlapped with the urban landscape might be considered as a marker of the entire phenomenon distributed around a place, creating a perceptible atmosphere for anybody located in this space [8].

The fundamental principle of the world-line considers the temporal structure of perception, claiming that an observer identifies the beginning and the end of a perceived event. This assumption states that the observer codes its corresponding time-segment, or world-line, as a causal attribute of the perceived event [10,11]. In our case, for a given subject and within a given observation period, soundscape knowledge of an observer is relevant to sound sources emergence and occurrence frequency. Those two subjective characteristics constitute the main scaling dimensions which have to be defined for informational quantization.

2.2. Entropy Index Dimensioning

Among various variables, the entropy is the thermodynamical simplest quantity to be applied to non-physical systems, as it is considered to be a measure of system disorder within informational datasets.

Unlike thermodynamic entropy, being a “content-full” concept specific to thermodynamic systems, statistical entropy applied here qualifies informational probability distribution as a “content-free” syntactic concept, a quantity calculated from the numerical properties of the “virtual system” distribution laws.

It is important to note that even Boltzmann’s view of the second law of thermodynamics, using the entropy term [12] as a law of disorder into an open system, confirms this “content-free” ontological status of statistical entropy [13].

Following this assumption, the challenge of the work pioneered by Shannon and Jaynes [14,15] was to extend the entropy concept and to apply its measure in as many different contexts as possible.

Therefore, Shannon’s information theory [14] together with E.T. Jaynes principle of Maximal Entropy [15] provides a constructive criterion for setting up probability distributions on the basis of partial knowledge. This criterion leads to a statistical inference model called maximum-entropy estimate.

2.3. Application: Soundscape Entropy Quantification

Sound source geo-localization (xy location into the urban maze), is gathered here with two spatial extends: sound pressure level and soundmark entropy values.

Equivalent Sound Level is formulated in terms of the equivalent steady noise level which in a stated period of time would contain the same noise energy as the time varying noise during the same time period [16]:

$$L_{eq} = 10 \times \log \left(\frac{1}{T} \sum_i 10^{L_{eq_i}/10} \times \Delta T_i \right) \quad (1)$$

The second indicator corresponds to Shannon entropy calculation [14] as:

$$H = \sum_{x \in X} p(x) \log \frac{1}{p(x)} \quad (2)$$

which describes the uncertainty quantity by the information which we do not have about the state occupied by the concerned source.

Probability $p(x)$ is based on empirical frequencies measurement issued from observation statistics from inquiries and soundwalkers expressions [17], and is actually calculated from the frequency occurrence of the related event x within the recorded soundscape; Huffman’s perceptual encoding can then be enacted through the relevant soundscape Zipf-Pareto law for the sources distribution [18].

The resulting quantity is a measure of the uncertainty of the soundscape events occurrence: the higher the H value, the more unpredictable the constitutive sound events; in other words, entropy index H constitutes a reliable soundscape originality measurement.

In our case, Maximum Entropy principle considering n sound sources as discrete random variables x_i with entropy H_i , the “largest remaining uncertainty probability distribution” can be estimated from the 2^{n-1} dimensional vector, called entropy vector $E(x)$, following equation (3) formulation:

$$E(x) = \frac{1}{n} \sum_{i=1}^n -\log p(x_i) = \text{Max}\{H_1, \dots, H_n\} \quad (3)$$

This quantity helps to study the behavior of the information taking into account the n sources composing the studied soundscape. The related quantity $E(x)$ gives us the extension value of the corresponding soundmark, considering its ability to reach the listener (source emergence value) during the corresponding urban soundwalk.

For a given soundscape, sensation scaling proceeds from “soundmarks” (maximum entropy sound event) to “Keynotes” (null-entropy background noise) [19].

2.4. Zipf-Pareto Law Sources Distribution Dimensioning

First applied for English texts word occurrence frequency determination, empirical law known as “Zipf law”, named for Harvard linguistic professor George Kingsley Zipf, models the occurrence of distinct objects in particular collections [20,21,22,23]. Zipf law says that the i^{th} most frequent object will appear $1/i^{\text{th}}$ times the frequency of the most frequent object in the collection. Moreover an expression of universal regularities, this law is applied in numerous domains: in English texts word occurrence frequency [20,24,25], as well as populations of cities [26,27,28], immune system characterization [29], bibliographical classification or prediction [30,31], or cancer classification [32]. Nevertheless, except musical [33,34,35] and audio medical signal [36] applications, we did not find Zipf law application for other audio domains such as soundscape acknowledgment in scientific literature.

Zipf’s law may be stated mathematically as:

$$\log(f_x) = C - s \times \log(k) \quad (4)$$

where f_x , the frequency of the unit (word form or lemma) having the rank k , s , the exponent coefficient (near to 1 for French language word frequency distribution), and C , a constant.

For soundscape application, mathematical expression of Zipf law involves the number of occurrences of a done sound source, understood as an acoustic emerging event. Within a given soundscape, relationship between the constitutive sound sources emergence with respect to their occurrence frequencies should then provide a rank-order Zipf power law, with a specified entropy-dependent slope. The resulting event density probability distribution will then provide information quantification through entropy indexing, thanks to the use of GearScape dedicated spatial semantic system.

3. Soundscape Geoprocessing

The main idea here is to take benefit from Geographical Information well-known concepts and techniques and apply them both to the spatial interactions between sound ambiances and an urban pedestrian walk. Therefore, we have to map soundmarks effects onto the pedestrian pathways and compute some relevant indicators to characterize the environmental interaction process. Among all of them, we have decided to focus on the spatial sound pressure integrated levels and the entropy index. The main add-on of this paper is clearly to couple soundscape emergence concept with a pedestrian mobility, that is to say a dynamic process. Confluence is achieved in the context of a specific Geographical In-

formation System called GearScape.

The data that have to be processed are purely of vector type. They are provided by the French IGN agency (layers extracted from the so called BD ORTHO® spatial database). The study areas have been selected because of their wide morphological variabilities concerning both the urban fabric and the corresponding networks.

As illustrated in **Figure 1**, the global spatial process we have designed concerning the Strasbourg use case is divided into 10 main steps combining some well-known OGC [38,39] functions. It consists in a sort of raster approach, which relies on an orthogonal regular grid based layer produced using an operator developed in the context of the UrbSAT plugin [40,41].

Unlike to the 1st approach, the 2nd one develops a rather different method (see **Figure 2**). Instead of meshing the surrounding soundscape it discretizes the soundwalks themselves. This processing schema is much more robust and efficient. This is the one we have adopted with the Nantes town centre use case.

4. Comparative Case Studies

4.1. Contexts

In this section we will successively apply and detail all the processes presented in section 3 to one of the main study area of the AMBIOFLUX project in Strasbourg suburbs and to the Nantes city center. First case study is located in the north suburbs of the French city Strasbourg (see **Figure 3**). It corresponds to a rectangular area of less than 2.9 km, from north to south, by 2.2 km, from west to east. In this region of interest, 5 different pedestrian pathways are defined with an average length of 4.7 km and a standard deviation equals to 1.2 km. All those pathways connect Schiltigheim city to Strasbourg’s railway station.

In addition to input data already mentioned, 7 soundmarks have been defined. In all corresponding locations, sound recording have been performed and analyzed for the 5 more significant ones.

After recording operation, qualitative analysis consists in operating a multi-sources description of the whole sequence. A statistic of the resulting description items will then provide their respective occurrence frequencies, in order to be plotted regarding their corresponding emergence levels.

Thereafter, a rank-order (Zipf) analysis has been processed taking each constitutive source within the sound marked sequence into account.

Second case study is located in Nantes historic heart, a west-coast located city in France (see **Figure 4**). Walks were led the same day evening, from town-hall to Roosevelt Court. The fourteen fixed recording sequences points have then been analyzed to compute Zipf

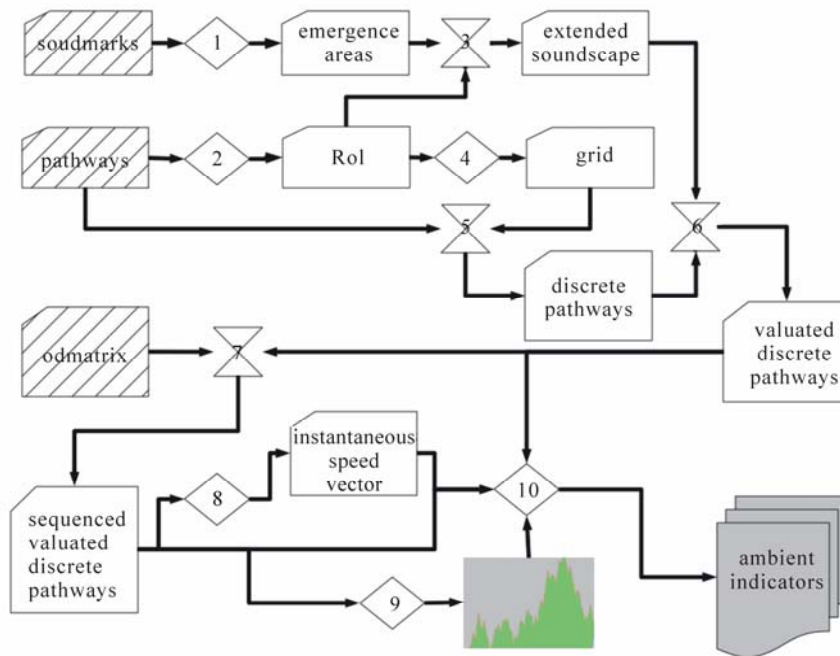


Figure 1. The processing schema we have adopted in the Strasbourg use case. The sequence is composed of 10 main operations. Input maps are 45 degrees wide hatched, intermediate results have no background color and final output results are colored in gray.

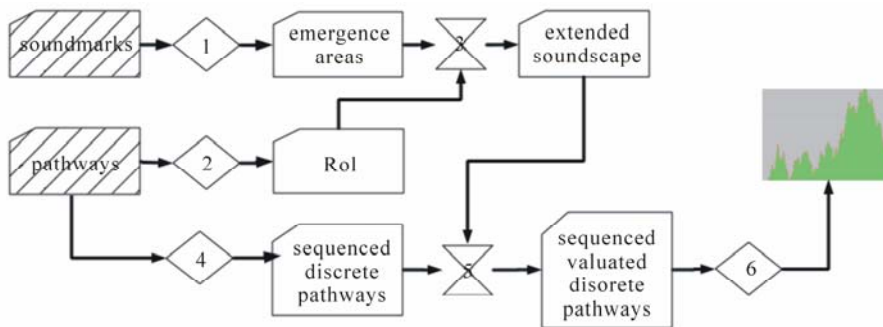


Figure 2. The processing schema we have adopted in the Nantes use case. The sequence is composed of 6 main operations. Input maps are 45 degrees wide hatched, intermediate results have no background color and final output results are colored in gray.

rankorder analysis and calculate the corresponding entropy values. The high density of analyzed points will enable a fine spatial discretization for soundmarks entropy evaluation, according to the perceived sources occurrence frequencies.

4.2. Results and Discussion

As illustrated by the low Zipf rank-order slope values of the **Figure 5**, emergence density probability distribution of the recorded points clearly discriminates poor soundscapes (“low-fidelity” soundscapes in the sense of M. Schäfer [6,19], corresponding here to points 1 (Rempart) and 3 (Autoroute de l’Est)), from rich ones (“high-fidel-

ity” soundscapes, composed with hierarchized numerous sound sources, corresponding here to points 5 (Cité Nucléaire), 6 (Schiltigheim) and 7 (Z.A. Mittelfeld)). As a result, we obtain a set of spatial punctual positions and, for each of them, ambient indicators such as the aggregated L_{eq} , coupled together with entropy evaluation. The numerical values we obtain are presented in **Figure 7**.

To characterize each studied pedestrian pathways, some ambient indicators are produced such as the aggregated L_{eq} or the maximum entropy value all along the pathway.

Concerning Nantes’s walkthrough area, calculated entropy values (see **Figure 6**) clearly discriminate three

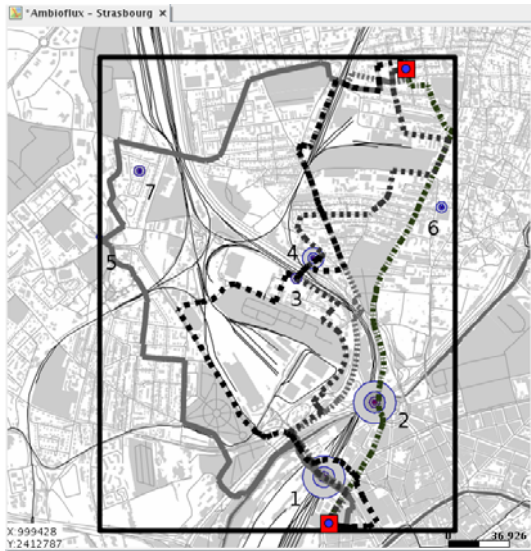


Figure 3. Zoom on the Region of Interest located in the north-west of the French city Strasbourg. All pedestrian pathways (dotted polylines) share the same origin (disc in a square, north of the map) and destination (disc in a square, south of the map) points. The seven soundmarks emergence areas are numbered and represented by pale gray concentric discs.

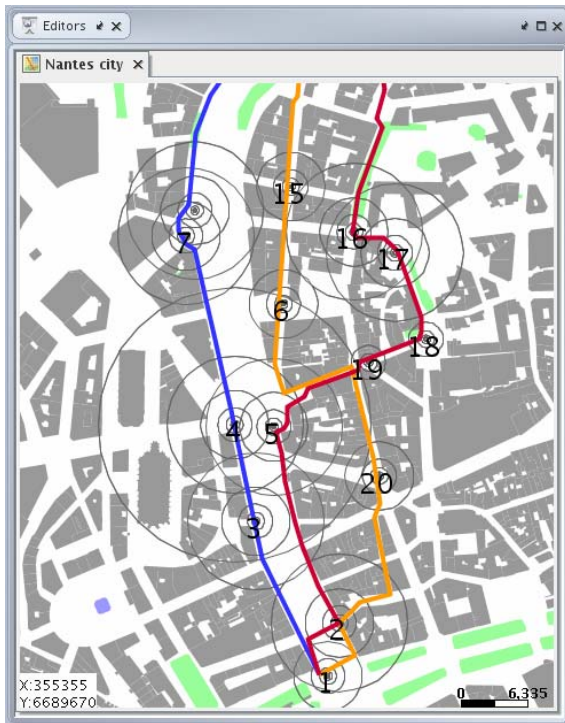


Figure 4. Zoom on the Region of Interest located in the town center of the French city Nantes. All pedestrian pathways share the same origin (north of the map) and destination (south of the map) points. The 14 soundmarks emergence areas are numbered and represented by concentric discs.

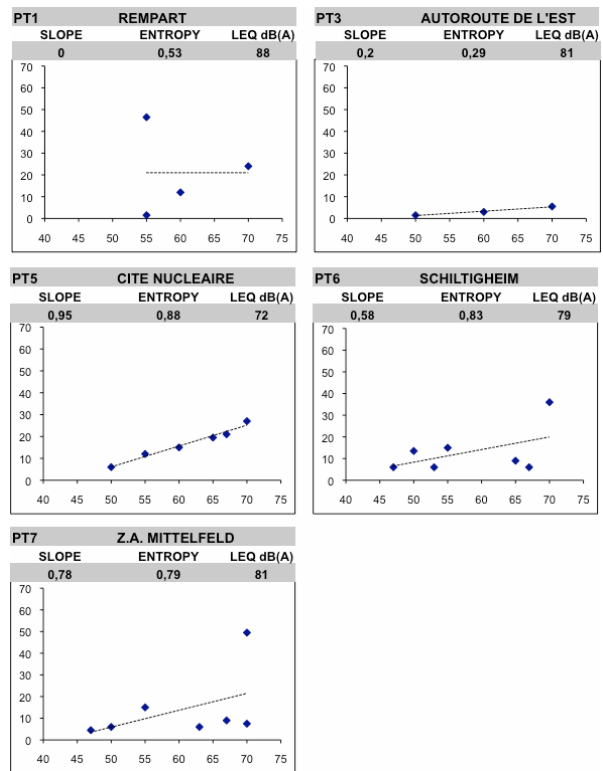


Figure 5. Zipf rank-order laws, entropy values and sound levels for soundwalk points in Strasbourg suburbs.

sets of soundmarks: a “low entropy group”, scaling values from 0.6 to 0.7 (points 3,4,8 and 15), a “middle” one, with entropy values from 0.7 to 0.8 (points 1,2,6,7, and 17) and a “high entropy group” gathering values over 0.8 (points 16,18,19,20). One can note that this values distribution is confirmed by the soundmarks Zipf rank-order laws, which regression values scales from 0.02 to 0.29 for the first group, from 0.2 to 0.5 for the second one, and from 0.4 to 0.5 and more for the “highest entropy group”.

Another remark concerns the relatively lower entropy values bracket for Nantes soundmarks, compared to Strasbourg’s ones. This fact can be explained by the difference of areas extensions: since Strasbourg’s area, dedicated to seven urban soundwalks analysis is about 6 km², Nantes area study gather fourteen points in about only 0.7 km². Consequently, high soundmarks density within this last area, concentrated in a relatively homogeneous urban district, can not offer the same sound ambience variations than the first one in Strasbourg.

As may be noticed, paths number 2 to 5 (see Figure 3) share the same maximum entropy value. It is due to the fact that they all come across the same predominant soundmark (south-most one, tagged as “Rempart”).

What seems important to notice here is that both

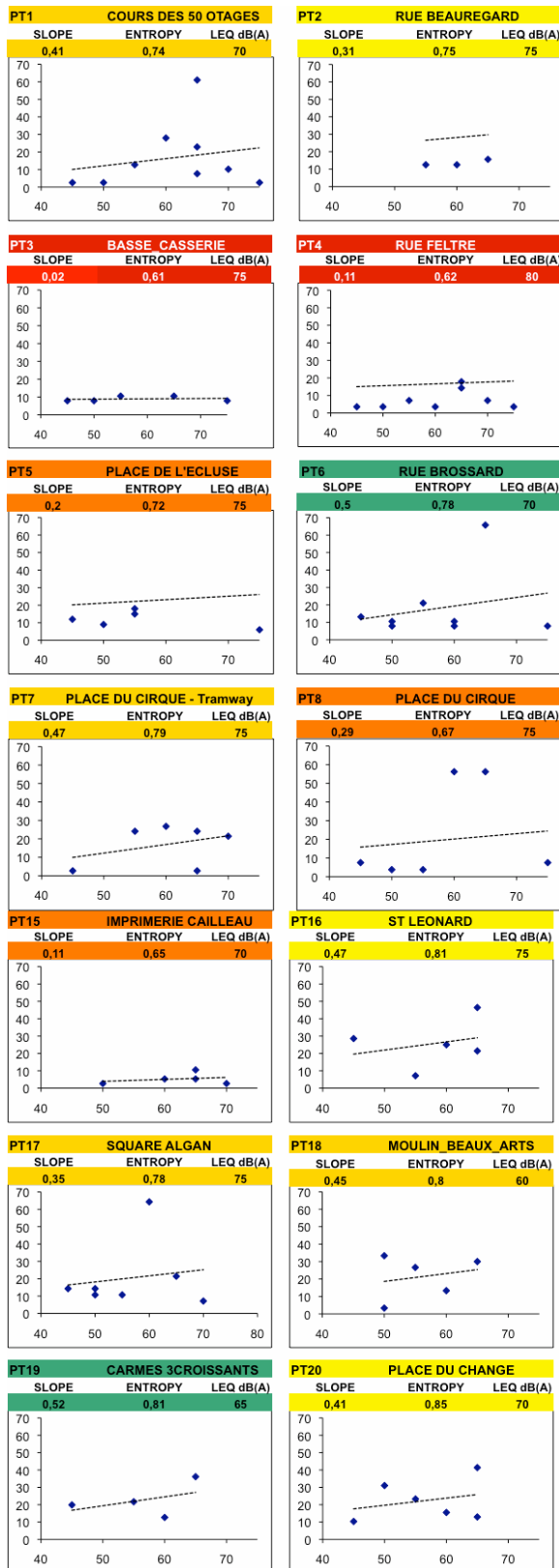


Figure 6. Zipf rank-order laws, entropy values and sound levels for soundwalk points in Nantes city center.

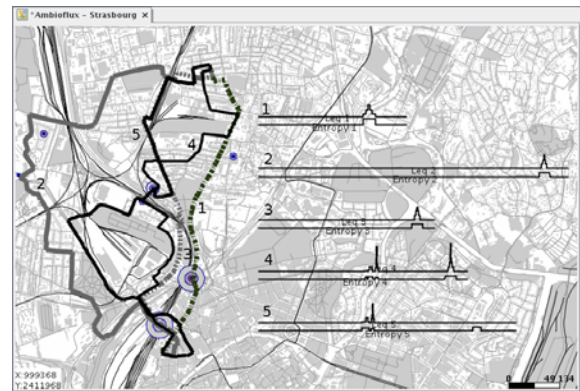


Figure 7. Time-line approach of the equivalent sound level and the entropy index of Strasbourg suburbs.

entropy and equivalent sound level signatures do not fully match in the particular case of the 5th pathway (see Figure 7). Indeed, crossing half the first soundmark emergence area (south-most one, tagged as “Rempart”), the “soundwalker” faces a particular acoustic event that is not significant in term of noise energy but in term of informational content (entropy). This clearly shows that entropy index is not strictly correlated with the equivalent sound level index.

For Nantes city centre area, informational treatment exposed in Figure 8 provides a time-sliced discreet quantitative information on the soundscape originality and intelligibility of the concerned sound environment during the walks. Thus, the “distance gap” between soundmarks (observation points) has to be well-dimensioned to obtain a continuous varying entropy signal. As observed here, a relatively dense soundmarks discretization within the urban space allows a quasi-coherent entropy signal along the soundwalk pathways.

5. Validation Method: Entropy vs. Soundscape Multi-sources Combination

5.1. Reference Model Presentation

In order to evaluate the stability of our method, we have decided to compare the results we obtained on the city of Nantes with an already published soundscape quality map. This map was aimed to produce sonic ambiances compositions during a soundwalk, constitutes a unique attempt of sound ambience qualitative analysis in scientific literature by Léobon in the 90’s [45]. This structural and phenomenological approach of Nantes city soundscape is based on environmental sources sonic signatures analysis.

In this approach, “environmental sound sources” composing our perception of the urban landscape are translated into descriptive items, which statistical analysis leads to a soundscape multisources cartography.

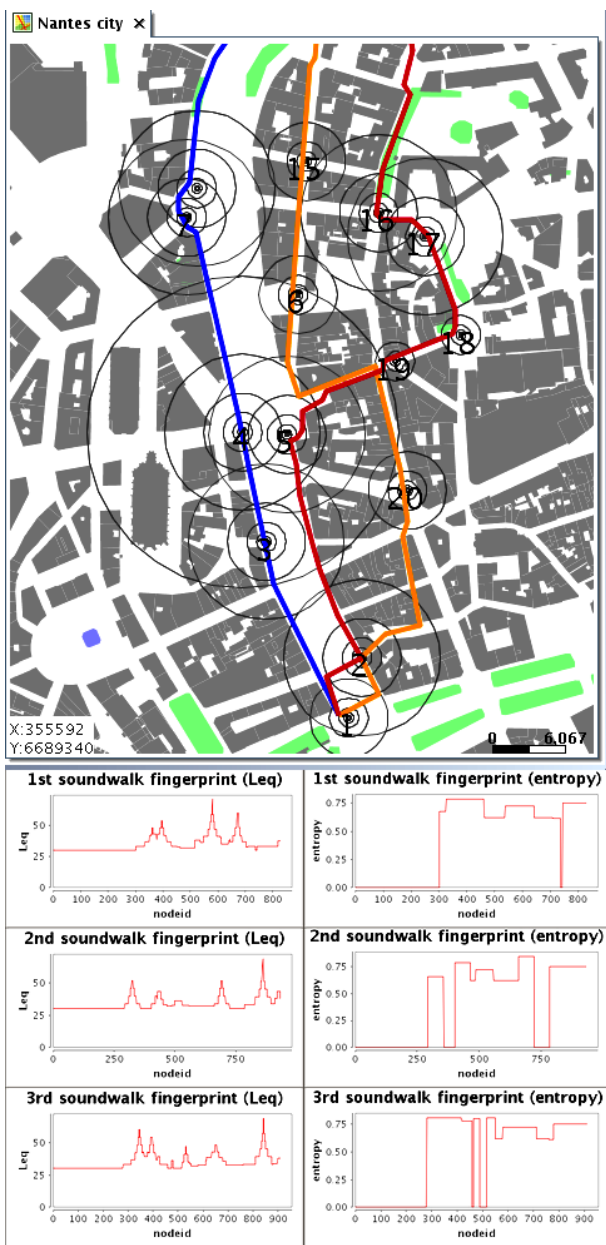


Figure 8. Time-line approach of the equivalent sound level and the entropy index of Nantes city center (The 1st soundwalk is blue colored, the 2nd one is orange colored, the 3rd one is red colored).

This reference qualitative sonic inventory is fed with urban soundwalks, marked out by relevant recording points, short sound sequences representing rather faithfully the districts’ various sonic atmospheres. Sampling of this soundwalk is relevant to an exploration process, discretizing urban space through obvious soundscape changes.

Each recorded sequence, examined through headphone

listening, is transcribed into a list of sonic items, grouped together according to sound sources families, thus constituting a hierarchic structure between three extreme uses of public spaces (as shown in **Figure 9**): the pedestrian sequence function (“*Présence*” in blue), the traffic line function (“*Activité Mécanique*” in red), and the animated places (“*Animation*” in yellow).

The cartographic mapping we reefer to associates a dedicated color to the corresponding area for each recording point within the soundwalks, according to the soundscape multi-sources composition. The ten colours used to represent the various sonic atmospheres of a city centre are the following (see **Figure 10**):

- 1) Blue: pedestrian, open spaces or residential sonic areas;
- 2) Purple: open spaces sonic areas with traffic noise in the background;
- 3) Green: mixed sonic areas with dominant anthropogenic noise;
- 4) Light green: mixed sonic areas with predominant anthropogenic noise, moderately animated;
- 5) Yellow: intensely animated sonic areas;
- 6) Salmon pink: mixed sonic areas with pedestrian and road traffic, without sonic signs of activity;
- 7) Light yellow: mixed sonic areas with pedestrian and road traffic, moderately animated;
- 8) Orange: mixed sonic areas with dominant road traffic noise;
- 9) Ochre: mixed sonic areas with dominant road traffic noise, animated;
- 10) Red: predominant road traffic noise.

5.2. Ambient multi-sources informational validation

The Nantes entropy and Zipf rank-order law calculations were produced with strictly the same points used for the reference sound ambience cartography we will present now. As we were part of this research [46], we used the

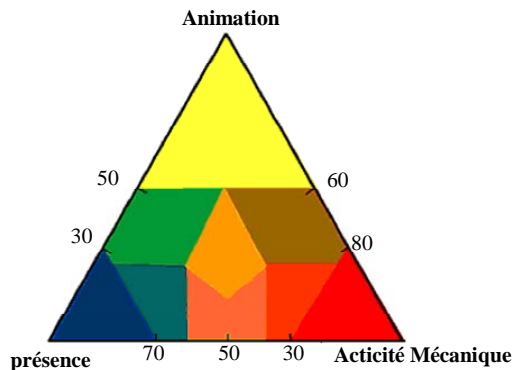


Figure 9. Sound sources color trade-off (extracted from [45]).

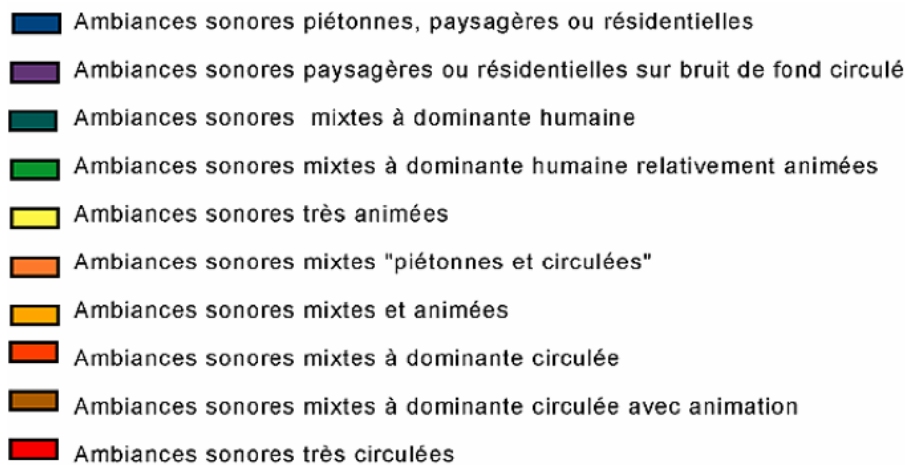


Figure 10. The ten colors used to represent the various sonic atmospheres of a city centre (extracted from [45]).

same audio samples to provide the previous informational computing: this enables direct comparisons between originality measurement (informational computing) and ambient multi-sources characterization (Léobon's methodology [47]).

The reference cartographic representation uses the previously described colors to indicate the composite multi-sources areas, as seen on the following sound ambience map, based on Léobon's summer evening soundwalks in Nantes city center (see Figure 11) [48].

Despite their short extends, those paths reveal various atmospheres that a passer-by would face when wandering in the urban maze. As a consequence of this case study limited area, the great density of analyzed points enables a very fine qualitative discretization of the paths for micro-structural analysis of the soundwalks.

5.3. Results Comparison: Entropy Values vs. Ambiance Multisource Qualification

In order to validate the maximum entropy values obtained all along the three pathways, we will compare them to the soundscape ambient multi-sources data, presented in the sound ambiances cartography Figure 11 above. To facilitate this data set comparison, we have re-used the color code already presented. Thus, in the Table 1, each row color corresponds to the characteristic of the corresponding soundmark.

In this case study, poor soundscapes correspond to red (areas with predominant road traffic noise) and orange (mixed areas with dominant road traffic noise) colors. Their respective entropy values scale from 0.61 to 0.75 for all the concerned points (points 1, 3, 4, 5, 8, and 15). A common characteristic of all those punctual positions is their high road traffic noise component, which tends to "annihilate" the other sound sources, and impoverish the corresponding soundscapes. Moreover, those points are



Figure 11. The Nantes city center sound ambiances on summer evening [48], including the 3 soundwalks paths and the recording punctual positions.

characterized with high sound pressure levels (around 75-80 dB(A)).

On the other side, soundscape richness is signed up with higher entropy values: the corresponding punctual positions display entropy values from 0.75 to 0.85 (points 2, 6, 7, 16, 17, 18, 19, and 20), signing more "anthropogenic" or "animated" soundscapes, as "pedestrian,

Table 1. Soundmarks attributes (Nantes' use case). Comparative table between the soundmarks informational characterization, multisource composition and sound levels. Color coding is refeering to the sound ambience cartography (see Figure 11).

PT.	SLOPE	ENTROPY	AMBIANCE DESCRIPTION	LEQ dB(A)
1	0,41	0,74	pedestrian and road traffic	70
2	0,31	0,75	pedestrian, road traffic and animated	75
3	0,02	0,61	predominating road traffic noise	75
4	0,11	0,62	predominating road traffic noise	80
5	0,2	0,72	mixed with dominant road traffic	75
6	0,5	0,78	mixed with dominant human noise	70
7	0,47	0,79	pedestrian and road traffic	75
8	0,29	0,67	mixed with dominant road traffic	75
15	0,11	0,65	mixed with dominant road traffic	70
16	0,47	0,81	pedestrian, road traffic and animated	75
17	0,35	0,78	pedestrian and road traffic	75
18	0,45	0,8	pedestrian and road traffic	60
19	0,52	0,81	mixed with dominant human noise	65
20	0,41	0,85	pedestrian, road traffic and animated	70

road traffic and animated areas” (light yellow color coded), or “mixed areas with dominant human noise” (light green). Sound level values of those points are mostly lower (around 65-70 dB(A)).

5.4. Discussion

Considering this sharp fitting between soundscape multisource characterization and their entropy evaluation, this approach allows to characterize soundscape originality in terms of “phonicity”, measuring the intelligibility of a soundscape, which is our ability to identify all its components. Moreover, we can notice that a noise level's map would fail to provide information as accurate about a district's sonic identity. The comparison between noise and entropy levels of the same sonic walk shows without contest that only this last can be able to discriminate very close sonic ambiances, taking both vehicle's traffic and pedestrian activity into account.

6. Conclusions

Reference map scales the gradual intensity variation of a sound quality in terms of soundscape multisource composition. This composite sound qualitative hierarchy, which human mind may express through an ordering scale, can be traduced by Zipf rank-order power law.

Next step of our work will study the entropy signal shape, more precisely its “remanence” component, which means the “memory effect” of soundmarks. This will enable to consider soundmark effect as a “non instantaneous” process (actually traduced through a squared entropy signal when the listener is entering the soundmark influence disc), with considering an “entropy decay”

when the soundwalker leaves the soundmark influence zone. Computation of this decay will be stated from the Zipf rank-order power law, considered as a 1/f sound source density distribution, in order to calculate a “soundmark emergence power spectrum”, able to provide a soundwalk continuous informational evaluation.

7. Acknowledgements

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