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Summary
In complex systems, log-log linear relations between appropriate descriptors are quite common. In this paper, the rural and urban soundscape is assumed the voice of a complex system. Self-organized criticality is shown to occur at different levels in this underlying system. The power spectral density of loudness and pitch in recordings of rural and urban soundscapes indeed often follows quite closely to the typical 1/f frequency dependence in many cases. Looking in detail at the data, a breaking point is observed in many of the curves around 0.2 Hz, which corresponds to a period of 5 seconds. It seems logical to associate this to within event and between event sound dynamics. Indicators based on this analysis could be useful for cataloguing soundscape dynamics. By extension of the earlier finding that 1/f noise is quite common in music, labels such as "*boring / dull*" or "*too chaotic / too unpredictable*" may even be borrowed to describe soundscape dynamics.

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1. Introduction

A number of almost historical papers [1, 2] have studied the long-term variations in level and pitch of different kinds of music that mankind has produced. They made the surprising observation that all of the musical genres that were studied showed the same 1/f behavior both for level and pitch variations. They also showed that artificial sound with these characteristics was recognized as "music" by a listener. Music with a flatter spectrum sounded too chaotic, too unpredictable. A steeper slope resulted in too much predictability and hence boring and dull sound. Speech fragments showed this 1/f behavior to a lesser extent.

These findings were so surprising that they have puzzled many. A linear dependence on a log-log scale emerges in the description of the dynamics of many complex systems [3]: the light from quasars, the intensity of sunspots, the current through resistors, the flow of the Nile, a pile of sand, stock exchange price indices, the use of words in English literature, critical ecological systems, etc. In 1987, Bak *et al.* [4] introduced the notion of self-organized criticality to explain 1/f noise. Although it is doubtful that their initial model actually succeeded in predicting 1/f dynamics, self-organized criticality (SOC) is now generally believed as a source of linear log-log behavior of complex systems [5, 6]. Therefore, in creating music, man seems to imitate the temporal fluctuation of self-organized critical systems, which are quite common in the (natural) living environment. In Section 2, we include a more detailed discussion of complexity and self-organized criticality.

Given the above observations it seemed obvious to look for 1/f-like features in the dynamics of urban and rural soundscapes. Traditional research on the impact of noise on the quality of the living environment and human health has focussed on indicators of average loudness as a primary indicator. A-weighted sound pressure levels are often used as an approximate measure that is much cheaper to obtain. A vast amount of information is now available on the relation between urban noise levels and major impacts on the human observer such as reported annoyance and sleep disturbance. However, designing an optimal urban soundscape involves much more than just preventing annoyance, sleep disturbance, or negative health impacts [7, 8, 9]. Several methodological procedures were proposed to evaluate and categorize soundscapes [10]. Based on psychoacoustics and sound quality theory, the relation between environmental sound and its perception can be clarified [11, 12]. In [13] the authors make a strong attempt to link acoustic and psychoacoustic parameters to the subjective appraisal of urban sound.

Dynamics of the sound may be an important factor in this process. New indicators are required to quantify this additional dimension. Percentile psychoacoustic loudness was proposed for this purpose [14, 13] but this neglects any cohesion between fluctuations in level. The 1/f behavior so common in music may be a good starting point for developing such indicators. The fact that music and urban soundscapes have been linked before [15] gives more confidence in the approach.

In this paper we only observe soundscapes and indicate possible indicators for cataloguing them based on their dy-

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namics. It is not the purpose of this paper to link our observations to perception of the soundscape by the human observer.

This paper is organized as follows. In section 2, complex systems and self-organized criticality are discussed with special emphasis on the mechanisms that may lead to 1/f behavior in soundscapes. Section 3 briefly describes the methodology used to obtain and process the data. Then, just to set the framework, a few music fragments are analyzed in Section 4. Finally, rural and urban soundscapes are addressed in section 5.

2. Complex systems and self-organised criticality

This section investigates where self-organized criticality can be expected in the urban and rural setting, and how this could theoretically lead to observing 1/f noise in its soundscape. The term complexity is used to describe a wide range of very different systems that have as a common feature that their dynamic behavior (or even their geometry) can not be reduced to a single or small number of oscillators and time constants. No general theory for treating complexity is widely accepted today. However, it is clear that complexity emerges when a sufficient number of weakly interacting systems form a "group" behavior. As stated in the introduction, many complex systems show a surprisingly linear relation in a log-log chart for some of their characteristics and self-organized criticality seems to be able to explain this [5, 6]. Simulations of swarm dynamics and interacting agents have shown that a common attractor combined with a closeness factor that can be exchanged between particles or agents, together with some damping are sufficient to create self-organized criticality [16].

Natural systems have been successfully described using the theory of fractals [17]. Self-similarity, that is the discovery of very similar shapes when zooming in or using a smaller ruler to measure, is an essential feature. The fractal dimension D is introduced to describe how sizes change when "zooming in". For time series, the fractal dimension, D, (as determined using the box counting method) is related to the negative slope of the spectrum, α, by [17]

$$2D = 5 - \alpha$$

if the 1/f$^{-\alpha}$ trend extends over the whole spectrum and $\alpha > 1$. A fractal dimension $D = 2$ thus corresponds to 1/f dependence. Brownian noise, another well-known dynamic, has $D = 1.5$ and shows a 1/f^2 dependence. White noise has $\alpha = 0$ and $D = 2.5$. This brief discussion on fractal dimension was introduced on behalf of those readers more familiar with fractal theory and self-similarity than with complexity and self-organized criticality. Both are clearly related, the former being more descriptive, the latter being more explanatory. Let us now turn to the main topic of this section, the identification of possible self-organized criticality (SOC) in the urban and rural setting that may influence soundscapes.

2.1. Wind

It is well known that low frequency wind noise can contribute significantly to outdoor noise measurements, especially in quiet areas. In [18] three causes of wind noise are identified: (1) turbulence generated at the microphone membrane; (2) intrinsic turbulence in the air flow (pseudo-noise); (3) indirect sound caused by rustling grass, leafs, etc. Since all soundscape recordings were done using adequate microphone windscreens and at sufficiently low wind speeds, contribution (1) can be neglected. In [19] Morgan *et al.* prove that for contribution (2) $P = \rho UV$, where V is the average wind velocity, U is the rms-value of the velocity fluctuation and P is the rms-value of the acoustic pressure. This is primarily a low frequency contribution. When focussing on the frequency range that contributes most to perception, secondary noise sources can easily be the dominant source in terms of sound pressure level. Experimental data gathered in open grassland [18] showed a relation $L_{A95} = 22.6\log(v) + 22.7$, where v is the 5 minute average wind speed. Wind induced noise in trees was investigated in [20] both for a single tree and several forest edges. For deciduous species (aspen, birch, oak) an average regression $L_{Ap} \sim 30\log(u)$ was found and for coniferous species $L_{Ap} \sim 35\log(u)$ seems to be a good trend. In these relations u is the average wind speed (averaging time 10 seconds to 1 minute depending on the site) and L_{Ap} is the 10 second / 1 minute averaged sound pressure level. It is also shown in the same reference that the wind induced vegetation noise spectrum does not change significantly with wind speed. In general, it can be concluded that although wind induced sound pressure depends on the degree of turbulence in the wind and on the vegetation that is present near the observation point, it is on average proportional to V^α. V is the average wind speed and α is a coefficient somewhere between 1.1 and 2.

Let us now turn to long term variations (seconds to minutes) in the wind speed. Turbulent flow is a typical example of a complex system showing clear scaling laws. The flow in the atmospheric boundary layer is turbulent. This turbulence is usually isotropic up to inhomogeneities of several meters in size. Three models for locally homogeneous and isotropic turbulence are commonly used in sound scattering studies: the Kolmogorov spectrum, the Gaussian spectrum and the Von Kármán spectrum [21]. For the purpose of this evaluation, the Kolmogorov spectrum can most easily be used. It predicts a $-11/3$ power-law for the three-dimensional spectral densities of random inhomogeneities in the inertial range. If it is further assumed that these inhomogeneities are transported by the mean flow, a $-11/9$ or approximate 1/f dependence of the local wind velocity fluctuation power spectrum is obtained. Based on the relation between wind speed and wind induced noise, 1/f dependence can be expected for the sound level power spectrum of type (2) pseudo-noise, while this dependence approximates 1/f^2 more for wind induced vegetation sound level. The assumptions on the temporal behavior of wind that underlie these theoretical considerations could not be backed up by experimental literature data. In particular, no data were found on the time scales of importance for this work. Therefore, wind velocity dynamics during recording will be verified explicitly in Section 5.

2.2. Water

The dripping of water from a tab has often been used to illustrate how complexity emerges at the border between order and chaos as the flow rate of water increases. The log-log linear behavior typical for self-organized systems has been observed in the flow of rivers. Therefore, it can be assumed that the power spectrum of the sound level fluctuations of the sound observed near running or falling water exhibits linear log-log behavior as well. An extensive literature search did not reveal the time scales on which this may occur.

2.3. Road traffic

Highway traffic flow near saturation has long been recognized as a system showing 1/f behavior. Several models were proposed to explain this characteristic [22, 23] and self-organized criticality (SOC) has been proposed as the mechanism. More recently the same dynamics were used for inner city traffic in a Manhattan block road system [24]. Well below saturation, the power spectral density of traffic flow intensity, Q, gets flatter, approaching the limit of white noise.

To translate this dynamic behavior to sound level fluctuations on a time scale of a number of cars passing, a few hypotheses are made. The average sound intensity, I, observed at the edge of the road scales linearly with traffic intensity, Q, if the dependence of sound power level on car speed is neglected as well as the individual differences between cars. In that case, the power spectral density of sound pressure level fluctuation is expected to show 1/f behavior. Since traffic bursts inevitably lead to lower driving speed and this has a considerable impact on noise emission at high speed, it is not expected that this relation is going to be exact.

At very low traffic densities, events occur randomly. This results in a long-term white noise characteristic for Q. The translation to noise levels is however no longer as straight forward. The slow growing and falling of the sound intensity of single cars passing has to be taken into account. If this intensity fluctuation for a single car passing is approximated by a Lorentz curve, the power spectrum will decay exponentially. On a log-log plot this shows as a stronger than linear decay as a function of frequency. The problem may however be obsolete since the soundscape will be dominated by other sources in that case.

2.4. Bird song

Intensity of bird song in the rural and suburban soundscape varies considerably during the day and strongly depends on the season. The ‘dawn chorus’ dominates the acoustics of the spring and summer early morning. This burst of bird singing has attracted the attention of many animal behavior scientists, but until today, no consensus is reached concerning its origin. In [25], 12 hypotheses are described and evaluated with respect to observed patterns: peak restricted to, and develops through the breeding season; qualitatively different signals used during peak; diel pattern varies among species. For the purpose of the research described in this work, it is noted that a number of hypotheses indicate an optimum for each bird individually independently of the presence and behavior of individuals of the same or a competing species. Recent research using stochastic dynamic programming [26] has given evidence in favor of the hypotheses that regulation of fat reserves and time spent on foraging and singing are related and can explain the increased song intensity at dawn, at least for some species. Spending excess fat reserves at dawn and inefficient foraging clearly result in an optimum that may occur at a slightly different moment for different species [27], but that is clearly the same for all birds of the same species. Additional hypotheses such as better propagation of acoustic signals, circadian cycles, and self-stimulation are at least partly supported by the evidence [25] and also result in the same optimum for all individuals of the same species.

Other hypotheses put forward for explaining the diel pattern of singing involve interaction between various birds of the same species. They include [25] territory defense, mate guarding, mate stimulation, and general social dynamics. These theories mention that dawn singing seems to be socially contagious (i.e. the behavior spreads from neighbor to neighbor), at least for some species and to some extend. It is also obvious that simultaneous singing has a disadvantage due to masking and nobody listening. It has indeed been observed that males singing to defend their territory stop singing occasionally during dawn bout to listen to their neighbors. It has even been observed that species living in the same environment that have similar songs, develop a non-overlapping diel pattern (i.e. they sing at intermediate times).

The above discussion suggests that at least during dawn chorus singing, the necessary ingredients are present to develop self-organized criticality: there is a common optimal state for all individuals (enhanced by contagious behavior) and a repelling force that prevents them from acting too similar. Moreover, in contrast to the mechanisms previously discussed, dawn singing directly involves sound in the creation of SOC. Therefore 1/f dynamics of loudness and pitch fluctuation can be expected.

It is not clear how bird song during more quiet periods of the day is affected by these mechanisms.

2.5. A mixture of urban activities

There is no clear evidence that the mixture of activities that determine the soundscape of the inner urban shopping and recreating area has self-organized criticality in it. However, at least some of the elements are present. Each

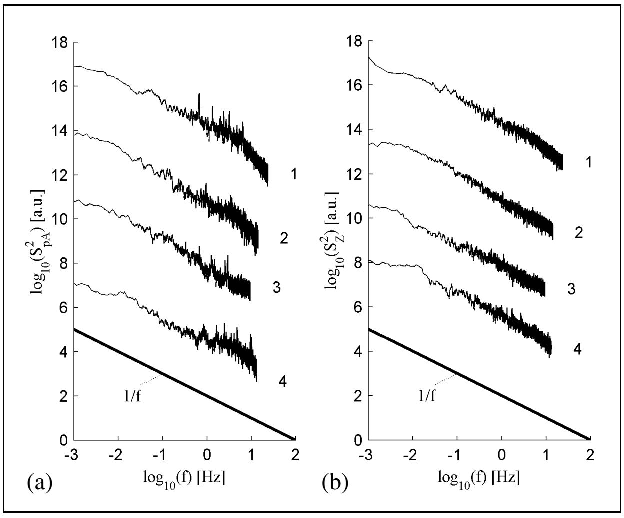

Figure 1. Spectrum of A-weighted sound pressure (a) and pitch (b) fluctuation of: 1. The 1st Brandenburgs Concerto by J.S. Bach; 2. The 2nd piano concerto by S. Rachmaninov; 3. Requiem by W.A. Mozart; 4. The 4 seasons by A. Vivaldi.

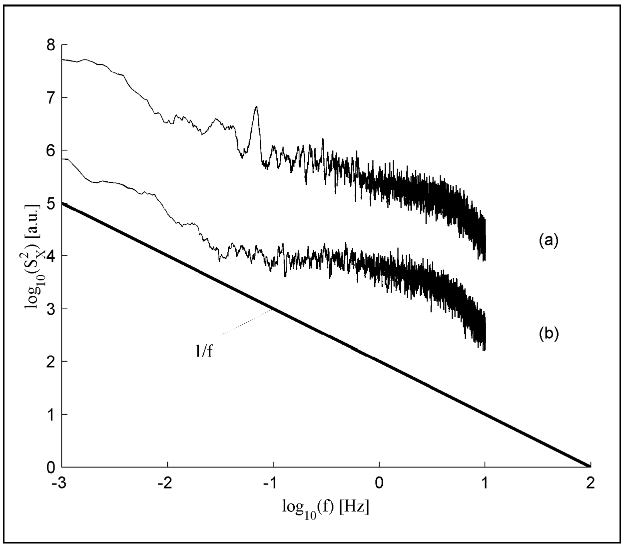

Figure 2. Spectrum of A-weighted sound pressure (a) and pitch (b) fluctuation in a speech fragment: "Het eeuwfeest" with Paul Van Vliet, Radio 1.

participant can be seen as an independent agent, each with its private goal. To some extent, they strive to a common optimum. There is some transfer of momentum leading to swarm-like behavior and finally there may be forces that repel at least some of the participants.

3. Methodology

Sound fragments of 15 minutes were used as basic material for this study. These were recorded monaurally on DAT tape using an omni-directional microphone. For further processing, these samples were stored as 16 bit PCM coded 44.1 kHz wav-files on computer disc. Since absolute amplitude may get lost in the process, simultaneous sound level measurements using standard equipment were performed during field recordings and later used for calibration. Three types of pre-processing were applied.

1. A-weighted level: Digital A-weighting filter followed by signal squaring, 1st order digital Butterworth filter with cut-off frequency 20 Hz (roughly corresponding to a 50ms averaging time), and down sampling by 200.
2. Loudness: Loudness calculation is based on the model proposed by Zwicker [28]. The implementation of the outer ear filter and 24 critical bands follows the approximations proposed in [29]. Pre-masking is neglected and a post-masking time constant of 100 ms is used. Time integration is based on a low-pass filter and a time constant of 40 ms as suggested in [28]. More accurate models for temporal masking [30, 31] are available today and recent findings on perceived loudness of fluctuating sounds may even indicate that available loudness models do not grasp the whole picture [32]. Although these more accurate models should be included in future analyses, we expect that this will not change any of the findings presented in this paper, where fluctuation over time intervals of more than 200 ms is of primary interest.
3. Instantaneous pitch: The signal is preconditioned by sending it through a steep band pass filter with cut off frequencies 100 Hz and 10 kHz. The instantaneous pitch is approximated by counting the number of zero transitions in 10 ms intervals similarly to the method used in [1].

The A-weighted level was included to allow the analyses to be performed on everyday sound level meters if required in future.

The power spectral density of loudness and pitch variations is obtained using the standard Fast Fourier Transform scheme, using a rectangular time window of length 15 minutes. The choice of time window is not very critical in this application. Finally, the curves obtained in the log(amplitude) versus log(frequency) domain are locally averaged over a symmetric interval that considers 11 close points.

4. Music and speech

For further comparison, the analyses of amplitude and pitch fluctuations in music and speech presented in [1] are repeated using the software modules described in Section 3. Figure 1 shows pressure amplitude and pitch fluctuations in 4 classical pieces. The duration of the fragments that were analyzed varies between half an hour and one hour. The resemblance to 1/f behavior is obvious. Small deviations at the lower frequencies are due to the finite duration of the sound samples. The flatter part below 10^{-2} Hz in "the 4 seasons" is caused by the fact that this music is composed of shorter fragments, each taking 100 to 150 s. Speech fragments behave slightly different (Figure 2). In the region 0.1 to 1 Hz the spectrum of pitch is almost flat, indicating the random sequence of frequencies in the spoken sentence. At lower frequencies, the 1/f de-

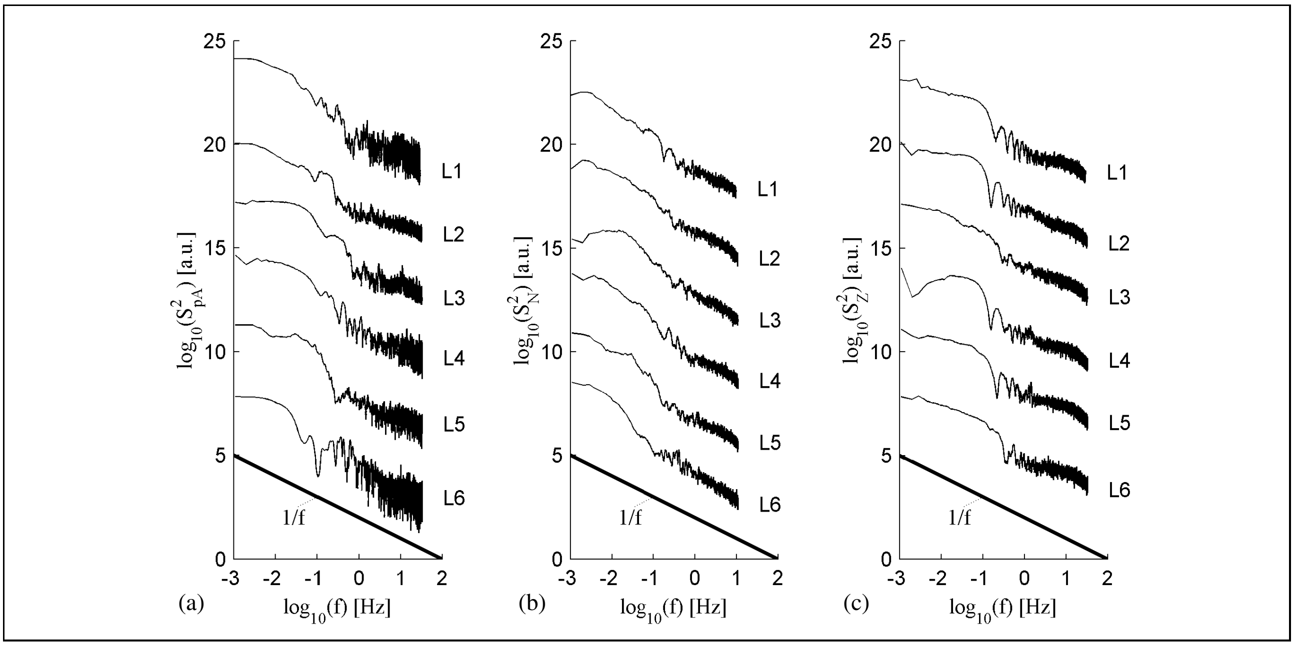

Figure 3. Spectrum of A-weighted sound pressure (a), loudness (b), and pitch (c) fluctuation for 6 rural soundscapes.

pendence is recovered indicating a complex sequence of high and low pitched voice passages.

The 1/f dependence of pitch and pressure fluctuation in music is explained by Voss *et al.* [1] as the result of a critical balance between predictability and novelty. Later this result was interpreted as music being an imitation of the self-organized criticality that seems so common in nature.

5. Rural and urban soundscapes

Based on the theoretical considerations given in Section 2, it was expected that the 1/f dynamics of loudness and pitch could also be present in outdoor soundscapes. Recordings were made at several different rural locations at different times of day. The A-weighted sound level, loudness, and pitch power spectra for a selection of 6 typical rural soundscapes (in Flanders, Belgium) are presented in Figure 3. Although the locations are specially selected as silent areas in Flanders (L_{Aeq} between 40 and 45 dBA), several man made noise events could still be detected in the recordings. Table I gives an overview of these events, grouped by category external, rural, and natural sounds. The commercial airplanes mentioned in the table, pass at considerable height resulting in a long, low level background event.

The spectra given in Figure 3 in general show 1/f behavior, but deviate much more from this characteristic than music. Loudness spectra seem to show a clearer trend than A-weighted pressure spectra. When amplifying the recorded soundscape, the silent periods become filled with (low frequency) sound that is probably caused by distant man-made noises such as traffic. It is well known that, under most meteorological conditions, sound in the frequency range of a few hundred Hertz propagates further than high frequency sound. A-weighting does not adequately remove these unheard components as Zwicker loudness [28] does so they may peak up in the Fourier spectrum of the amplitude fluctuation. Above 0.2 Hz, loudness decreases as 1/f but at longer time scales the frequency dependence can be quite different. It is believed that this is due to the few loud events that increase the contribution of slow variations. Pitch changes are also more important below 0.2 Hz and are relatively independent on frequency above this limit. A limited number of events (probably planes) changing the pitch slowly, combined with relatively unpredictable pitch variation within the event, can explain this.

Table I. Noise events observed during rural soundscape recordings.

event	L1	L2	L3	L4	L5	L6
external						
distant traffic	yes	yes	yes	yes	yes	yes
train	1	1	1		1	
Airplane sport	2		1		1	2
Airplane military				3		1
Airplane commercial	4	6	3	4	6	5
Loud recreation						5
rural						
Local cars		1	2			3
Farm noises	2	5	10	2	2	2
Agriculture machine				1		
Farm animals	5	15	25	15	15	5
natural						
Birds	yes	yes	yes	yes	yes	yes
Insects						
Wind noises						
Water						

Table II. Description of the urban settings where soundscapes were recorded.

label	description
G1	Quiet green residential area in the center of town, medieval built up area preventing intrusion of city sounds, occasional car, a few groups of talking people and playing children around.
G2	Residential area at the edge of town, close to green open area, some maintenance activity, a few people around, occasional bird, occasional airplane.
G3	Narrow street canyon, shops and offices, with car traffic (close to saturation) and streetcar. Talking people passing by.
G4	Tourist attracting embankment in the car free center of the city. Many pavements with people talking, laughing, some bicycles and walking people, distant music.
G5	Open square in the center of town with very restricted car traffic, but with public bus traffic and a streetcar passing every few minutes, occasional bell. People sitting and talking at the many outdoor restaurants and pubs, one of them singing loud during part of the observation time.
G6	Open square with a few trees. Inner city traffic (close to saturation) and people passing by although often near the edges of the square.
G7	Traffic free shopping street, crossing street with traffic close by. Several delivery trucks pass close by in this small street canyon and some unloading is going on. People passing by, sometimes talking, an occasional biker, church bells ring for a few minutes.
G8	Blocks of flats in open green setting just inside the ring road which is relatively close by, occasional car passing between the blocks, playing children, occasional passers by.
G9	Park area with private villas, railway station and two major roads entering the city. A lot of park birds, pigeons, a few playing children, a few local cars.
G10	Inner city residential area, closely built up, a few trees, cars coming in, stopping, leaving. There is also some building activity, some church bells can be heard in the distance, occasionally small groups of talking people on foot.
G11	One of the most important shopping streets with dense stream of lively talking people passing. No car traffic, but an occasional streetcar.
G12	Blocks of flats in open green setting near the major city sporting facilities, including water features and bushy areas. Important local traffic at short distance, several airplane, occasional loud recreation, in general an unexpectedly busy area.

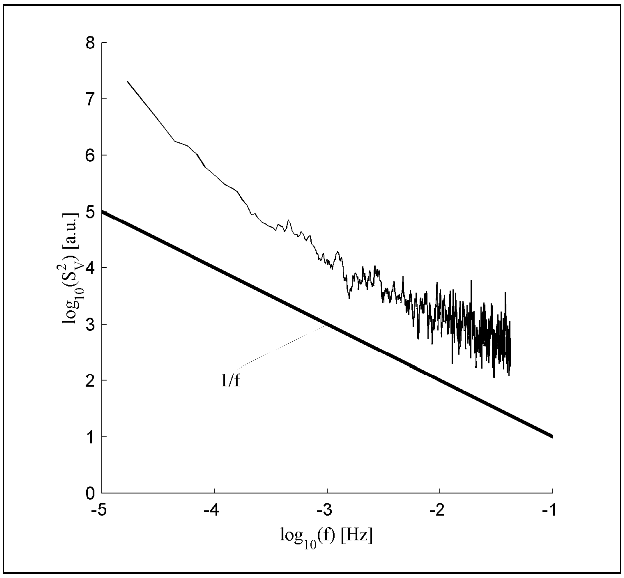

Figure 4. Power spectrum of wind velocity fluctuation observed during the period that soundscapes were recorded.

Although wind induced noise was not dominantly present in any of the soundscapes, it is still of interest to see that the wind velocity fluctuations observed at a fixed location in the measurement area (measurements made at 10 second intervals) have a power spectral density function following the 1/f law, at least down to about 10^{-3} Hz (Figure 4).

Urban soundscapes were recorded in the city of Ghent, Belgium. In Table II the sites where soundscapes were recorded are described. The power spectra of fluctuation in A-weighted sound pressure, loudness, and pitch are shown in Figure 5 for these 12 soundscapes. The general 1/f trend is again obvious. As for the rural soundscapes, the loudness fluctuation spectrum gives a clearer picture than the A-weighted sound pressure fluctuation spectrum. For urban soundscapes, just as it was the case for rural soundscapes, often a breakpoint seems to occur between 0.1 Hz and 1 Hz.

In an attempt to reduce data for further analyses, the frequency interval is therefore split into two parts: I_1 = [0.002Hz, 0.2Hz] and I_2 = [0.2Hz, 5Hz]; $I_3 = I_1 + I_2$ is the full frequency range. I_2 corresponds to a time interval between 200 ms and 5 s and can therefore be seen as characteristic for the sound fluctuations emerging from the source itself (the song of birds, voices, or the changes in the murmur of a passing plane). I_1 corresponds to the interval between 5 s and about 10 min. It is therefore influenced mainly by sources such as cars, trains, planes, or talking people passing the observer. In each interval, the slope, α, of a linear fit on the log-log chart is calculated

Table III. Slope α and quadratic error e of a linear fit on the loudness spectral density in the three frequency-intervals.

		I_1		I_2		I_3	
	L_{Aeq}	α	e	α	e	α	e
L1	44.3	-1.64	0.56	-0.95	0.55	-1.16	0.56
L2	42.6	-1.54	0.47	-0.94	0.57	-1.13	0.58
L3	42.2	-1.57	0.51	-1.06	0.55	-1.26	0.55
L4	43.3	-1.96	0.54	-1.01	0.57	-1.26	0.58
L5	40.9	-2.11	0.63	-0.91	0.55	-1.20	0.57
L6	48.7	-2.16	0.55	-1.26	0.55	-1.31	0.56
G1	51.0	-1.33	0.51	-0.88	0.55	-0.97	0.55
G2	54.4	-1.17	0.47	-0.94	0.56	-1.06	0.56
G3	65.5	-0.88	0.56	-0.91	0.55	-1.14	0.56
G4	62.8	-0.54	0.49	-0.86	0.55	-0.94	0.55
G5	65.1	-0.94	0.63	-1.18	0.58	-1.17	0.58
G6	74.0	-1.67	0.65	-0.87	0.57	-1.12	0.58
G7	57.7	-0.78	0.53	-1.06	0.56	-1.15	0.56
G8	59.7	-0.56	0.40	-0.82	0.56	-1.04	0.57
G9	51.3	-1.17	0.59	-0.91	0.55	-1.04	0.55
G10	57.3	-1.73	0.53	-1.09	0.57	-1.14	0.57
G11	65.3	-1.22	0.50	-0.92	0.56	-1.05	0.56
G12	50.9	-1.11	0.48	-0.84	0.55	-1.08	0.56

Table IV. Slope α and quadratic error e of a linear fit on the pitch spectral density in the three frequency-intervals.

	I_1		I_2		I_3	
	α	e	α	e	α	e
L1	-1.49	0.53	-0.93	0.55	-1.21	0.57
L2	-1.71	0.66	-1.06	0.55	-1.23	0.56
L3	-1.00	0.41	-0.86	0.56	-1.09	0.57
L4	-1.56	0.70	-0.89	0.55	-1.14	0.57
L5	-1.35	0.41	-0.76	0.56	-1.04	0.57
L6	-0.98	0.21	-0.74	0.57	-1.07	0.58
G1	-1.20	0.62	-0.85	0.58	-0.83	0.58
G2	-0.57	0.26	-0.81	0.55	-1.03	0.55
G3	-0.64	0.32	-0.94	0.57	-1.14	0.57
G4	-0.75	0.34	-0.81	0.55	-1.06	0.56
G5	-0.19	0.25	-1.09	0.54	-1.16	0.54
G6	-1.41	0.51	-1.04	0.56	-1.24	0.57
G7	-0.89	0.41	-0.90	0.56	-1.08	0.56
G8	-0.42	0.19	-0.99	0.56	-1.22	0.57
G9	-0.81	0.40	-1.04	0.55	-1.21	0.55
G10	-1.50	0.56	-1.18	0.55	-1.29	0.56
G11	-0.86	0.39	-1.02	0.55	-1.06	0.55
G12	-0.54	0.37	-0.99	0.53	-1.13	0.53

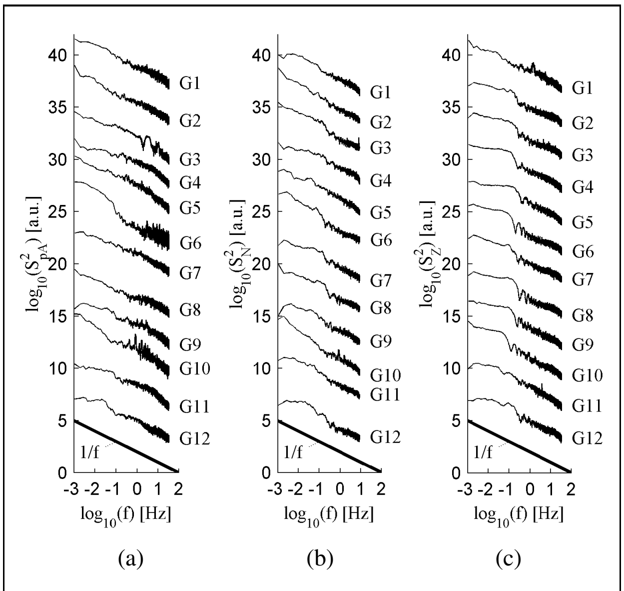

Figure 5. Spectrum of A-weighted sound pressure (a), loudness (b), and pitch (c) fluctuation for 12 urban soundscapes.

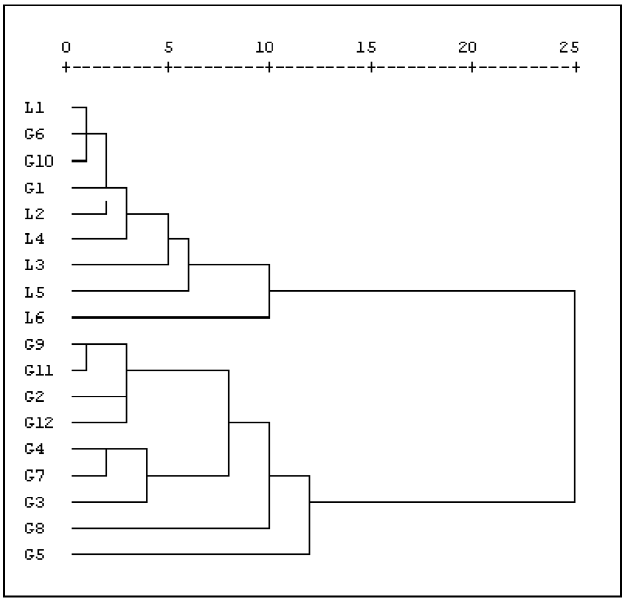

Figure 6. Dendrogram showing the result of hierarchical clustering based on average within group linkage.

together with the squared fitting error, e. This is done both for the loudness and for the pitch fluctuations and thus results in twelve possible indicators for the dynamics of each soundscape. The result is given in Table III and Table IV. For loudness, the α's obtained for frequency interval I_2 are sufficiently close to -1 to call this behavior 1/f by common convention. For pitch, soundscapes L5 and L6 seem to behave somewhat different. In the lower frequency interval I_1, more variance in the α's is observed.

Clustering of the soundscapes based on sound levels leads to a grouping of quieter and louder soundscapes. Since the power spectral density of loudness and pitch and in particular its slope gives additional information on the dynamics of the soundscape, clustering based on the 12 indicators derived above may uncover another dimension. Hierarchical clustering using the SPSS software [33] based on within group linkage is performed. Figure 6 gives the results if Pearson's correlation is used as a measure of linkage. In this figure, linkage between groups of soundscapes further to the right indicates a weaker coupling. Two large groups emerge. One of them contains all rural soundscapes and a selection of urban settings. In particular G6 and G10 remain members of this group for various other choices of the parameters used for hierarchical clus-

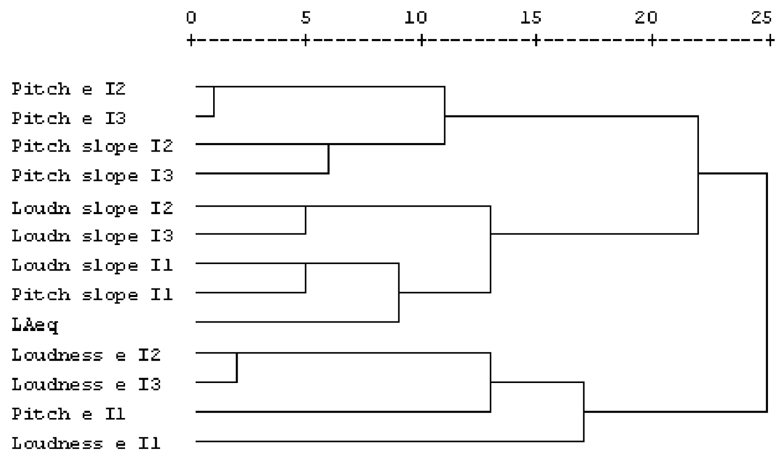

Figure 7. Dendrogram showing the result of hierarchical clustering based on average within group linkage.

tering. At first sight, these urban soundscapes have nothing in common with the rural setting. G6 in particular has a very high L_{Aeq}. Clustering plots showed that the interval I_1 is the most important discriminator between the two large groups. All rural soundscapes and the urban settings G6, G10, and to a lesser extend G1 have in common that a few sound events peak considerably above a more constant background noise. In the urban soundscape G6, this background is quite hurly-burly but when the recording is played back more quietly, the similarities to suburban soundscapes become obvious.

There are clearly too many indicators extracted to describe the shape of the power spectral density of loudness and pitch fluctuations for them to be of any practical use.

Principle component analyses including rotation, resulted in four underlying variables explaining 78% of the variance in the data. The grouping of variables did not result in easily interpretable conclusions. The second component includes L_{Aeq} and combines it with slopes in loudness and pitch spectra in interval I_1. Hierarchical clustering based on the same method as used for soundscape clustering also allows clustering variables. The result is represented graphically in Figure 7. It is clearly observed that the variables extracted for interval I_3 do not add much information to the variables extracted for I_2 since they are always grouped in an early stage (at the left hand side of the figure). L_{Aeq} seems to be very close to slopes in power spectral density of loudness and pitch for the interval I_1. This is probably because both are an indication of the presence of (loud) events in the soundscape.

6. Discussion and conclusions

Theoretical considerations led to the conclusion that self-organization is so common in many of the activities that together generate the rural and urban soundscape, that a linear behavior on a log-log scale of the power spectral density of loudness and pitch fluctuations had to be found in sound recordings made in these settings.

The most important finding of this paper is that the expected 1/f behavior, previously found in music, also appears in many soundscapes. However, this conclusion should be refined. It is quite common to find 1/f in the frequency interval [0.2Hz, 5Hz]. That is the region corresponding to time scales of the order of a few seconds. It is dominated by fluctuations in pitch and loudness of the source itself. On longer time scales, that is in the frequency interval [0.002Hz, 0.2Hz], the power spectrum differs significantly. In all rural soundscapes there are more slow variations in loudness and pitch than expected in the case of SOC. This is an indication of predictability and is caused by single cars and planes passing by and heard from far away. Some of the urban soundscapes show this same characteristic although they may be much louder on the average. In other urban soundscapes 1/f or even a flatter spectrum is observed in this frequency interval. Therefore, self-organization may indeed be more common here. It can be attributed to traffic flows near saturation, mainly heard at a distance in the soundscapes that were studied or flocks of people passing in shopping or busy entertainment areas.

For cataloguing, indicators based on loudness and pitch power spectrum log-log linearity corresponding to time intervals longer than 5 seconds are of interest since they tend to be more complementary to average loudness and L_{Aeq}. However, from a perception point of view, higher frequencies, thus shorter time scales may be more indicative.

It is not the goal of the present paper to interpret these observations in terms of perception. Future work will have to draw this connection. From findings with music, some indications can however be given. On the shorter time scale ($< 5\,\mathrm{sec}$), the 1/f observed in many of the soundscapes indicate that their dynamics is quite interesting. For some of the rural soundscapes the pitch power spectrum is too flat (e.g.L5 and L6). In terms of the music results, this indicates that the pitch is too chaotic, not predictable enough.

For longer time intervals, the loudness slope in most of the rural soundscapes is steeper than 1/f. Again extrapolating the findings from music, this is an indication of too much predictability. This may be identified as boring in terms of loudness. The loudness dynamic in most of the urban soundscapes is less predictable as indicated by a 1/f or even flatter frequency dependence. In the latter case loudness dynamic may even start to sound too chaotic, to unpredictable to be music-like. The reason for this dependence may be quite different as indicated by the two examples G4 and G8. It could be very instructive to link this unpredictability, especially in time intervals corresponding to I_1, to the mitigating effect of *predictability* on the harmful effect of noise on man [34] in future research.

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