The rhythm of the urban soundscape*

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The rhythm of the urban soundscape has traditionally been studied focusing on negative effects on man, such as noise annoyance and sleep disturbance. Recently a more holistic approach, including positive and negative aspects as well as non-residential functions of the urban environment, has gained renewed interest. The label “urban soundscape” is often used to refer to this approach. Research towards selection and quantification of the acoustic descriptors of the urban soundscape is, however, still in an early stage. This paper draws on the analogy with music and self-organization to propose an indicator for studying the temporal structure of the urban soundscape. Applicability is illustrated by drawing a map of music-likeness of the soundscape in an urban area.

1. Introduction
During the past few decades studies on the effect of noise on man have focused on physical and mental health, and its relation to noise level. In many situations the unwanted health effect or annoyance can be related to one particular intruding sound. Soundscape research takes a more holistic approach. The acoustic environment is regarded as an aggregate of many sounds that can evoke specific emotions. The soundscape is seen as an integral part of the living environment, interwoven within the whole context of visual environment (landscape), perceived air quality, feeling of safety, etc. Mismatch between different components of the living environment, including soundscape, may be at least partly responsible for a negative evaluation of its quality.

Urban soundscapes emerge naturally as a result of the typical activities that take place in the public area. Over time, urban soundscapes have evolved. Today, in many cases road traffic noise dominates the soundscape, often implying impoverishment of the living environment. Therefore, soundscape design should be included in future urban mobility planning, which requires the use of soundscape quality indicators. To describe the outdoor acoustic field, some indicators have become very commonly used. The average sound level \( L_{Aeq} \) is traditionally used as a primary indicator because it is easy to measure and to calculate and correlates reasonably well with perceived loudness and specific annoyance. For non-specific, retrospective noise annoyance rating of the immediate vicinity of one’s dwelling, night (and evening) seems to play an important role. Hence \( L_{dn} \) (or \( L_{den} \)) is chosen as a suitable indicator for long-term assessment.

Validating new indicators which relate physical measurements to noise perception and evaluation is one of the current challenges in the area of soundscape research. A number of principal components can be found in the subjective evaluation of soundscapes. Generally speaking, loudness-related cues come out as an important component, but factors related to the spectral and temporal structure also often emerge. Sound quality measures have been suggested for soundscape analyses since they tend to capture loudness, spectral content and short time fluctuations in a way that is more closely related to subjective preference. Although often mentioned in relation to noise annoyance, studies on the influence of supra-second temporal structure have been very rare.

This paper relates urban soundscapes to music and self-organization, and presents an indicator for studying the temporal structure of the urban soundscape. Applicability is illustrated by drawing a map of music-likeness of the soundscape in an urban area.

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2. Music, self-organized criticality and urban soundscapes

When one thinks of music and temporal structure, the term rhythm almost naturally comes to mind. Rhythm can be described as the variation of the duration of sounds over time, or as the collection of all periodic events that constitute the sound. In Western music, rhythms are usually arranged with respect to a time signature. Different time-scales in music can be distinguished, from the basic units of musical structure, single notes, to musical phrases and movements. Environmental soundscapes are essentially manifestations of rhythmic systems. Measures to describe rhythm in music can therefore provide good criteria for analyzing (urban) soundscapes. In natural and urban sounds, time structure at the micro-level—a few seconds and shorter—is typically associated to variations within one acoustic event. Time structure at the macro-level is caused by the succession of acoustic events.

In a holistic approach, Voss and Clarke studied the temporal structure of music by looking at the power spectrum of the temporal envelope of various pieces of music. In this type of spectrum, peaks reveal periodic events, e.g. a loud note played about every 10s will give a peak at 0.1Hz (note the difference with the commonly used audio spectrum, which equals the power spectrum of the sound wave). Rhythmic structures on macro-level as well as on micro-level can be analyzed in this spectrum. It was found that, on a log-log scale, the spectra for many of the musical genres considered were linear; moreover the slope always corresponded to 1/f at the macro-level down to the length of the piece. This means that music has a structure on all different time-scales, and that these scales are distributed roughly logarithmically in time and have comparable amplitude variations at each level of structure. For example, there could be four notes to a phrase, four phrases to a theme, three repetitions of a theme in a development, three developments in a movement etc. Furthermore, it was observed...
that most listeners found artificial 1/f-type music the most pleasing, compared to artificial music showing a flatter (more chaotic and unpredictable) or a steeper (more dull and boring) spectral slope. Figure 1(a) shows a few examples of envelope spectra for different musical genres. In view of application of this technique for outdoor sound, the short-time A-weighted level time series of the acoustic signal can be used as the temporal envelope.

To explain the ubiquitous occurrence of 1/f noise in nature theoretically, Bak et al. introduced the notion of self-organized criticality, which is now generally believed to be a source of linear log-log behaviour of complex systems. So in creating music, man seems to imitate the temporal fluctuation of self-organized critical systems, which are quite common in the (natural) living environment. Based on the above observations, it must be concluded that the spectrum of the temporal envelope of a sound fragment reveals important characteristics. Moreover, it seems reasonable to assume that a straight spectrum in a log-log chart and in particular a 1/f characteristic contributes to the pleasing character of the sound. By extension, this feature could be an interesting descriptor of urban soundscapes. In earlier work, it was shown that 1/f spectral characteristics could indeed be found in the temporal envelope of natural, urban, and rural soundscapes. Figure 1(b) shows a few selected examples where this characteristic is quite obvious. The observation of 1/f noise in these sounds becomes far less surprising when recognizing the complexity in the underlying systems. As examples we mention that self-organized criticality was proven to occur under certain conditions in the passage of cars on a highway and that several reasons can be given why it may also arise under quite mild conditions in the passage of talking people or in the dawn chorus of birds or the sound of wind blowing in trees. It is needless to say that many urban soundscapes may show a much less appealing temporal pattern, mainly due to the dominating presence of road traffic noise.

The relationship between appealing temporal structure of an urban sound and impact indicators such as sleep disturbance or noise annoyance is not trivial. Interestingly, music-like temporal structure may become quite disturbing or annoying when it intrudes unwantly into ones living environment. It is even reasonable to assume that a more predictable, boring, and dull temporal structure is preferred in this case.

3. Descriptor for the temporal structure of a soundscape

A descriptor for the temporal structure of a soundscape is proposed, which measures the similarity of the spectrum of its temporal envelope to those typical for music. Several choices need to be made. The time interval of interest spans from a few hundred milliseconds to several minutes. The critical difference between time structure at the micro- and macroscale was already pointed out. For music, this distinguishes the time structure determined by single notes from that determined by the musical phrase and longer length scales. Comparing the shorter length scale to urban noise seems less trivial because of the prevalent presence of rhythm in music. Therefore, the time interval of interest is selected from 5s to roughly 10 minutes, corresponding to the frequency interval [0.002 Hz, 0.2Hz]. The descriptor must further include not only the average slope of the spectrum in this interval, but also a measure of its linearity (on a log-log scale). The latter is described by the quadratic deviation from the best-fitted straight line.

Careful investigation of the spectra in Figure 1 shows that the so-called 1/f slope found for music is not all that strict. It may be more appropriate to state that the temporal envelope spectrum of music has an approximate 1/f or a 1/f-like behaviour. To quantify this vague statement, a fuzzy set containing all slopes $\alpha$ that are found in music is appropriate. The fuzzy set membership function is constructed on the basis of the probability distribution of slopes, derived from the spectra of musical fragments. To extract this probability distribution, 15 samples of music of different genres were analyzed. The smoothened membership function of music-like spectral slope, $\mu_\alpha(\epsilon)$, is shown in Figure 2(a). Much in the same way, the deviation $\epsilon$ of the spectrum from a straight line is approached. Smaller values of this deviation are more music-like, leading to the inclusive fuzzy set membership function, $\mu_\beta(\epsilon)$, shown in Figure 2(b).

Evaluation of degree of music-likeness of the temporal structure of a soundscape is based on the fitted slope $\alpha$ and on the deviation from a straight line $\epsilon$ of the temporal envelope spectrum. Set membership degrees (values of the membership function) close to one mean perfect inclusion or a very music-like slope or deviation. Membership degrees close to zero mean that the slope or deviation is very unlike that of music. The logical conjunction, stating that for the...
soundscape to be music-like, the slope as well as the deviation has to be music-like, is evaluated using the product fuzzy $t$-norm, resulting in the following formula for the music-likeness $ML$ of the temporal structure of a soundscape:

$$ML = \mu_A(\alpha) \cdot \mu_E(\varepsilon)$$

As an illustration, Table 1 contains a verbal description of a selection of most and least music-like soundscapes out of recordings at 45 locations. Not surprisingly, the most music-like samples contain a variety of sounds from only weakly correlated sources. The least music-like ones are often dominated by a single source. In some cases this source is present most of the time (e.g. busy traffic), in other cases the source produces only a small number of loud events per hour (e.g. train noise). Natural soundscapes that show a very music-like temporal pattern were often not very quiet ones. Very quiet natural sites got rated worse because the constant background hum was too predictable in comparison to the temporal structure of music.

The generally accepted feeling that fluctuating noise is more annoying than continuous noise, led to the construction of a number of indicators for sound exposure that include a measure of level fluctuation. Examples are the traffic noise index or the noise pollution level, both a linear combination of percentile levels. For 31 soundscapes, music-likeness was compared to $L_{A90}-L_{A50}$ as a classical indicator of dynamics. Some expected correlation was found ($r^2 = 0.25$), since quiet environments disturbed by the occasional loud event have a

Table 1. Selection of most and least music-like soundscapes out of 45.

<table>
<thead>
<tr>
<th>Label</th>
<th>Description</th>
<th>ML</th>
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</thead>
<tbody>
<tr>
<td>R8</td>
<td>Rural environment, sounds of birds, sometimes sounds from farm animals and a few farming activities, no local traffic, some distant traffic noise, occasional commercial aircraft at high altitude</td>
<td>1.00</td>
</tr>
<tr>
<td>U9</td>
<td>Traffic free shopping street, talking people passing by, occasional biker, distant murmur of urban traffic, occasional church bell</td>
<td>1.00</td>
</tr>
<tr>
<td>N3</td>
<td>Rocky coast, waves breaking, little wind, occasional insects and some people silently passing by</td>
<td>1.00</td>
</tr>
<tr>
<td>U11</td>
<td>Urban park in residential area, distant traffic with occasionally distinguishable events, wind in trees, a few birds, few local cars</td>
<td>0.95</td>
</tr>
<tr>
<td>U16</td>
<td>Urban street canyon in residential area, 400 to 600 vehicles per hour</td>
<td>0.05</td>
</tr>
<tr>
<td>R12</td>
<td>Rural area, number of loud recreational events, low flyover of military aircraft, sounds of birds, distant road traffic</td>
<td>0.05</td>
</tr>
<tr>
<td>R14</td>
<td>Rural area close to railway, natural sounds and wind in trees are most important noise sources between train passages</td>
<td>0.05</td>
</tr>
<tr>
<td>U23</td>
<td>Busy highway in open area at a distance of about 100m</td>
<td>0.00</td>
</tr>
</tbody>
</table>
low score on being music-like while at the same time $I_{50} - I_{90}$ is high. However, the proposed descriptor seems to probe a different dimension of the soundscape than these prior indicators. It was found that soundscapes with very similar statistical level distributions (possibly shifted in mean level) can have a quite different envelope spectrum. Examples are the rustling of wind in trees and the noise of a highway; the former contains more slow variations and is more music-like than the latter.

It is our opinion that the relationship between the proposed descriptor for urban soundscape temporal structure and music, and the proven effect of music and music-like noise on mental state and possibly on health, are sufficient to justify its introduction. Nevertheless, it is interesting to find out how the temporal structure of the soundscape influences the evaluation by an accidental user of its urban context. In a small-scale face-to-face questionnaire survey involving 100 subjects and 10 urban sites, randomly drawn passers-by were asked about the character of the sound they heard, including its temporal structure. A comparison with the measured music-likeness of the soundscapes at the sites indeed showed some correlation with subjective rating for temporal structure and confirmed some of the observations made by trained acousticians. However, the trend was not that pronounced, indicating a strong influence of other (personal) factors on the evaluation.

4. Soundscapes dominated by road traffic noise

In Table 1 it was observed that many of the soundscapes with non-music-like temporal structure were dominated by traffic noise. If it is impossible to remove road traffic noise from large urban areas, one may want to manage traffic flows in such a way that they contribute as much as possible to a music-like temporal structure. It is not unreasonable to expect that there exists a flow pattern that results in a $1/f$ spectrum, since self-organized criticality has been observed in traffic.

Some insight is gained by analyzing traffic flows analytically. Assuming a flow of identical vehicles passing by along a straight road at randomly distributed instants, the temporal structure of the sound pressure level
only depends on the distance from the observer to the road axis, on vehicle speed and on traffic intensity. The spectrum can be obtained analytically by Fourier transformation of the Lorentz-curve\(^\text{10}\). For realistic parameter combinations the spectrum is rather flat in the frequency interval of interest, indicating chaotic and unpredictable temporal structure. Random vehicle pass-by instants is not very realistic unless vehicle intensity is so low that there is no interaction between the vehicles. Another extreme traffic model assumes that the distance between vehicles is constant. This makes the temporal structure periodic with a periodicity that reduces as traffic intensity increases, resulting in a peak in the envelope spectrum at the frequency corresponding to this periodicity. From the soundscape perspective, this implies that in this second extreme traffic model also the temporal structure is far from music-like.

Experimental studies involving traffic flows being very difficult to realize, a computational model for urban traffic noise was used to investigate the temporal structure of the noise of more realistic traffic flows\(^\text{11}\). The model couples microscopic traffic simulation, in which vehicles are modeled as independent entities mimicking realistic driving behaviour, with a vehicle noise emission and propagation model. Part of the city of Ghent was modeled in detail; the map showing the music-likeness of the soundscape is shown in Figure 3. Even when considering road traffic as the single noise source, the picture already looks quite complicated. The reason for this is that traffic dynamics may become complex, with traffic intensity characteristics that cause noise levels to fluctuate in a music-like way. This situation is found at intensities close to road saturation. Furthermore, sound propagation plays an important role, since a music-like temporal structure is often found in backyards.

5. Conclusions

The temporal structure of an urban soundscape can accurately be described by looking at the spectrum of the temporal envelope. Since it was noticed that particular spectral features that relate to self-organized criticality are present in most types of music (so-called 1/f noise) it is enlightening to look in particular for this feature in the temporal structure of urban soundscapes. By combining the requirement that the spectrum must show a straight line on a log-log scale and that this straight line must have a 1/slope for the temporal structure to be music-like, an indicator for music-likeness was constructed. Environmental sound recordings were tested for this temporal structure and indeed it was found in several natural and urban environments. At the same time soundscapes with far from music-like temporal structure are also quite common. For this latter group, two situations occur: either the temporal structure is too predictable or it is too chaotic. In general it can also be observed that music-like temporal structure is much more rare in soundscapes dominated by a single source.

Traffic noise is an important contributor to many urban soundscapes. Using microscopic simulation of traffic, it has been shown that traffic noise can become music-like, possibly caused by self-organized criticality emerging in the underlying traffic system. Unfortunately this is not a very common situation in urban traffic noise; traffic flows often seem to be too random or too structured. Randomness is caused by local generation of traffic. Traffic management in general, and traffic lights in particular, tend to regulate flow in a more deterministic manner.

The indicator presented in this paper sheds new light on how urban soundscape quality might be assessed in an objective way. By using the analogy with music, the indicator follows more closely the original ideas behind urban soundscape research. Based on this, we argue that the proposed indicator is a good candidate for describing and categorizing soundscapes temporal structure, and can be used in addition to loudness and spectral-quality indicators (sharpness, roughness).

However, there is an obvious need for further analyses of the relationship between these objective indicators and more subjective evaluations of the quality of urban sound by an active participant.

References


