A psychoacoustic-based methodology for sound mass music analysis

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Abstract. A *sound mass* is a specific state of the musical texture corresponding to a large number of sound events concentrated within a short time and/or frequency interval. Conceptually, it is associated with the work of György Ligeti, Krzysztof Penderecki, and Iannis Xenakis, among others. Recent studies have investigated *sound masses* via perceptual models, such as *Gestalt* models of perception and *auditory scene analysis*, and also from a more acoustic and psychoacoustic perspective obtained through audio recordings. The main goal of this paper is to propose a methodology for the musical analysis of *sound mass* music through audio recordings. We apply this method in the analysis of a performance of the first movement of Ligeti's *Ten Pieces for Wind Quintet* (1968), and explore relationships between the obtained audio descriptors and Ligeti's concepts of *timbre of movement* and *permeability*, in order to reveal Ligeti's strategies when dealing with musical texture and *sound masses*.

Keywords: sound mass music, musical analysis, audio descriptors, psychoacoustics

1 Introduction

This paper introduces a computer aided musical analysis methodology anchored on audio descriptors. Specifically, psychoacoustic models are applied to study *sound mass* composition. *Sound mass* composition emerges in the context of discussions about perception and 20th century serial music [19]. Noticeably, these discussions were part of the *Darmstädter Ferienkurse*, where composers attended classes and lectures on psychoacoustics, phonetics, information theory, and sound synthesis [5]. Some well-known examples of *sound mass* compositions are the large number of attacks in Ligeti's *Continuum* (1968), the micropolyphony and cluster techniques in his *Chamber Concerto* (1961), and the mass created by *glissandi* and extended techniques of the string orchestra in Xenakis' *Aroura* (1971).

The central idea in *sound mass* composition is to emphasize perceptual features of sound, by exploring the continuum of time and frequency domains to produce sound

* Micael Antunes is supported by FAPESP Grant 2019/09734-3. Jônatas Manzolli is supported by CNPq Grant 304431/2018-4 and 429620/2018-7. Marcelo Queiroz is supported by CNPq Grant 307389/2019-7.

textures with a high level of fusion and inner movement. Perception of *sound masses* is often linked with the limits of sound integration by the ear [19] and *microtime* perception [3]. *Sound mass* music is also associated with Huron's perceptual principles of *minimum masking, pitch proximity and limited density*, which are anchored in the *critical bandwidth* psychoacoustic model [17, 26].

Previous works have studied Ligeti's *sound mass* composition from a perceptual perspective, mainly through the *symbolic analysis* of the score. Clendinning explored such a perceptual approach in the study of Ligeti's compositional techniques such as *pattern-meccanico* [10] and *micropolyphony* [9]. Cambouropoulos [8] used *Gestalt* theory to investigate links between Ligeti's techniques and their perceptual outcomes, an approach already explored by Ferraz [14]. More recently, Douglas et al. [12] investigated *Continuum* (1968) within the context of Bregman's *auditory scene analysis* [6].

Methodologies anchored in audio descriptors with a psychoacoustic approach, which emerged in the context of computational and systematic musicology [23, 36, 21], have also been used to study Ligeti's works [21, 2, 1]. In this paper, we propose a methodology for musical analysis [36] focused on perceptual concepts that motivate *sound mass* music composition, associating them with descriptors derived from audio recordings. Specifically, we study Ligeti's viewpoint on *sound mass* composition through the concept of *timbre of movement* [19], associating it with *loudness* [13] and *roughness* [31]. Due to the correlation between spectral information and the perception of pitches and individual voices [17], we also investigate the use of *spectral entropy* [25] and *spectral irregularity* [7], associating them with Ligeti's concept of *permeability* [19, 2, 1, 3]. We present an musical analysis of the first movement of Ligeti's *Ten Pieces for Wind Quintet* (1968), using score-based information alongside the audio signal of a particular performance of this piece. We also derive representations based on audio descriptors that allow us to discuss Ligeti's compositional strategies and their perceptual aspects, as well as the formal development of the piece from the viewpoints of *timbre of movement* and *permeability*.

In Section 2, we lay out the theoretical background for this study, starting with an exposition of the concepts of *timbre of movement* and *permeability*. Then, we give an overview of the first movement of the *Ten Pieces for Wind Quintet*, followed by a review of the audio descriptors used in this work. In Section 3, we outline the analytical methodology proposed, and in Section 4 we present and discuss the results of our study. Finally, in Section 5, we present our conclusions.

2 Theoretical background

2.1 Ligeti's concepts of *Timbre of Movement* and *Permeability*

Two relevant György Ligeti's concepts associated with *sound mass* music composition are *timbre of movement* and *permeability*.

The concept of *timbre of movement*[3] refers to the achievement of fusion in musical texture by mixing a large number of sound events [19, p. 169]. Ligeti associates this

[3] In the original, Ligeti uses *timbre du mouvement* in French and *Bewegungsfarbe* in German [19, p. 169].

concept with his collaboration with Gottfried Michael Koenig in the electronic studio of the Westdeutscher Rundfunk (WDR) in Cologne [19]. To him, the most meaningful knowledge acquired in the studio was the observation that sound samples or synthesis components merge into a single texture when the number of sounds surpasses a certain threshold of our perception. This occurs when our auditory system can no longer discern the individual components of a musical texture, leading our attention to the global features and inner movements of *sound masses* [19, p. 169]. Ligeti used this concept of *timbre of movement* in his instrumental compositions with the *micropoliphony* technique [9], which allows achieving dense textures by overlapping a large number of melodies with short notes.

The concept of *permeability* refers to a state in which we are unable to distinguish pitches and individual voices. According to Ligeti: *"The loss of sensitivity to intervals is at the source of a state that could be called permeability"* [19, p. 123]. This concept is mainly associated with the use of *tone clusters* in his works, such as *Lux Aeterna* (1966). According to Ligeti, the tone cluster *"is somewhere between sound and noise and consists of several voices stratified and interwoven in semitones, which thereby give up their individuality and become completely dissolved into the resultant overriding complex"* [20, p. 165].

2.2 First movement of the Ten Pieces for Wind Quintet

Ten Pieces for Wind Quintet was composed in 1968, and dedicated to the Wind Quintet of the Royal Stockholm Philharmonic Orchestra. Each movement was conceived as a *micro concerto* with *tutti* odd movements and *solo* even movements, each solo being dedicated to one of the performers [33]. We choose as analytical corpus, for all feature extraction and section division, the version of the piece performed by *London Winds* in the album *Ligeti Edition 7: Chamber Music*, recorded in 1998.

Vitale [33] presents a thorough score-based analysis of this work, and highlights the gradual processes appearing in the piece, based on micropolyphonic strategies to generate the musical texture, where the musical material is articulated with slow modifications in pitch, timbre, density, and rhythm [33, p. 2]. Using as criteria pitch register and dynamics, this author proposes a division of the score of the first movement of the *Ten Pieces for Wind Quintet* (1968) in two main sections (Section 1: measures 1 - 16; Section 2: measures 16 - 22) followed by an appendix (measures 22 - 25). This corresponds respectively to the following time segments in the London Winds recording: 0:00.000 - 1:32.367 (Section 1), 1:32.367 - 1:58.390 (Section 2), 1:58.390 - 2:17.048 (Appendix).

2.3 Audio descriptors

The use of audio descriptors in the context of musical analysis is a multidisciplinary task [36] which admits a multiplicity of approaches depending on the context in which it is applied [21, 23, 36]. In this work, we design the analytical methodology anchored in audio descriptors for two main reasons: 1. audio descriptors provide a perspective (in our case, a perceptual perspective) on the musical sound data, allowing a better understanding of the musical composition [23]; 2. graphical representations of audio descriptors guide the listening throughout the analysis and facilitates the observation of related perceptual concepts [11]. As detailed in Section 3, we associate the concepts of *timbre of movement* and *permeability* with four audio descriptors: *loudness*, *roughness*, *spectral irregularity* and *spectral entropy*.

Loudness - *Loudness* is a psychoacoustic measure of sound intensity, usually associated with the perception of *dynamics* [3] in musical analysis. The total *loudness* of a time frame (segment of an audio signal) is based on Zwicker's *critical bandwidth* model [37, 7]. The specific *loudness* of each *Bark*[4] band can be computed by a simplification of the original equation [27] as

$$\text{Loudness} = \sum_{z=1}^{N} E(z)^{0.23},$$

where $E(z)$ is the energy in the z-th *bark* band for the time frame considered.

Roughness - According to Vassilakis [31], *roughness* is a perceptual feature related with the sense of very fast amplitude variations in the sound and it is partially conditioned by both the sound stimulus and the properties of the basilar membrane. The *roughness* value of a time frame is based on an approximation, proposed in [30], of the Plomp & Levelt experimental dissonance curve[5] [28]. For complex sounds, the *roughness* value can be computed using a formulation by Vassilakis, which embodies the physical and psychoacoustic mechanisms involved in its perception, as

$$\text{Roughness} = \sum_{i=1}^{N} \sum_{j=i}^{N} \frac{(a_i * a_j)^{0.1}}{2} \left(\frac{2a_j}{a_i + a_j} \right)^{3.11} \left(e^{\frac{0.84|f_j - f_i|}{0.0207 f_i + 18.96}} - e^{\frac{1.38|f_j - f_i|}{0.0207 f_i + 18.96}} \right),$$

where f_i is the i-th partial of the sound and a_i its corresponding amplitude.

Spectral Irregularity - The *spectral irregularity* feature used in this work was proposed by Krimphoff et al. [18] as a measure of the noise content of the spectrum [7, p. 60]. It is usually computed for each time frame in the magnitude spectrum as

$$\text{Irregularity} = \sum_{k=2}^{N-1} \left| a_k - \frac{a_{k-1} + a_k + a_{k+1}}{3} \right|,$$

where a_k is the value in the k-th magnitude coefficient and N is the total number of frequency bins in the spectrum.

A low *irregularity* value denotes a spectrum whose energy is concentrated in few frequency bins, associated with distinguishable components in the sound. In contrast, a high *irregularity* value implies a more regular energy distribution across all frequencies, associated with a more noisy content [7].

Spectral Entropy - *Spectral entropy* is an audio feature used for estimating signal information and complexity in the Time-Frequency Plane [15]. Higher *entropy* values are usually associated with higher spectral activity along all frequencies, and lower values are related to a concentration of spectral energy on few components.

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[4] *Bark* is the unit of Zwicker's *critical bandwidth* model [37].

[5] For a full revision on *roughness* curves, see [31].

The *Spectral Entropy* descriptor is derived from Shannon's information theory equation through an analogy between signal energy densities and probability densities [34], as

$$\text{Entropy} = -\sum_{k=1}^{N} P(E_k)\ln(P(E_k)),$$

where $P(E_k)$ denotes the relative frequency of the energy present in the k-th bin.

3 Methodology

Sound mass music, as already pointed, is intrinsically related to the perceptual outcome of the musical events [26, 12, 3]. Therefore, any musical analysis focused only on the score would not provide all relevant information for the understanding of *sound mass* features [3]. It is our aim to devise an appropriate approach to *sound mass* music analysis, based on information extracted from a musical performance through derived audio features. In order to do that, we propose a methodology for *sound mass* music analysis using audio descriptors and psychoacoustic features associated with Ligeti's musical concepts, aligned with score-based information.

The concept of *timbre of movement* is associated with the dynamic perception of the global behavior of musical texture and its *microtime* manifestation [29, 1]. The *loudness* descriptor is used as a measure for *global perceptual dynamics* [3] and the *roughness* descriptor was used to describe the *microtime behavior* of *sound masses* [1, 31].

According to the principles of *minimum masking* and *limited density* [17], the higher the level of spectral information in the auditory nerves, the lower our ability to perceive musical pitches and intervals. Therefore, the concept of *permeability* is represented by the *textural information level* of the *sound mass*, associated with *spectral entropy* [4], and the *noise content*, associated with *spectral irregularity* [7].

Based on the above concepts and their interrelationships, the analysis was conducted in 3 steps: 1. Manual segmentation of the audio signal according to the score, as described in Section 2.2; 2. Computation of the selected time-varying audio descriptors (Section 2.3), their corresponding graphical representations, mean and standard deviation values, as well as scatter plots to illustrate their correlations; 3. Musicological (human conducted) analysis of the piece to establish the relationships between musical content of the different sections and the obtained descriptors values.

Feature extraction was done using Python[6] and the Jupyter[7] environment. *Loudness*, *irregularity* and *entropy* were computed from the magnitude spectrogram obtained using Librosa [24], with a window size of 4096 samples and hop length of 1024 samples. The *roughness* descriptor was obtained from the reassigned spectrogram [16] (with the same parameters described above), as it depends on precise frequency and amplitude values. All the code used to extract and plot the audio features is available at a Gitlab repository[8].

[6] `https://www.python.org/`
[7] `https://jupyter.org/`
[8] `https://gitlab.com/Feulo/ligetis-wind-quintet-analysis`

4 Results and Discussion

Figure 1 corresponds to the graphical representations of the descriptors obtained from the audio analysis as functions of time. Each different color represents one of the three sections of the score: blue is the first section, orange the second section and green the appendix. Mean and standard deviation values for each descriptor and section are presented in Table 1. The analysis was conducted in 2 stages: first we explore the characteristics associated with *timbre of movement*, followed by the behavior associated with *permeability*.

Timbre of movement - According to the methodology proposed (Section 3), the psychoacoustic descriptors of *loudness* and *roughness* are associated with the concept of *timbre of movement*. Each section of the piece displays a different behavior in terms of this concept.

The first section displays a somewhat regular fluctuation of *loudness* values (blue line in the upper left corner of Figure 1). Within the same section, *roughness* (blue line in the upper right corner of Figure 1) displays low values with low variation. The corresponding statistics can be seen in Table 1.

In evident contrast with the first section, the second section of the piece displays the highest values of *loudness*. We highlight that, although the standard deviation values for these two sections are not very different, by inspection of the *loudness* curve, we can see that the first section has an oscillatory behavior while the second section displays an ascending pattern. Also, in the second section we observe the highest values of *roughness* with a complex oscillatory pattern, with spikes that go upwards towards the end of this section. Finally, the appendix presents low values and low variation for both *loudness* and *roughness*.

Section	*Loudness*	*Roughness*	*Irregularity*	*Entropy*
1	41.87 ± 14.49	9.96 ± 5.86	63.54 ± 40.72	0.42 ± 0.13
2	66.36 ± 12.52	103.12 ± 62.44	171.63 ± 58.37	0.74 ± 0.15
3	13.36 ± 5.29	0.55 ± 0.56	9.98 ± 6.58	0.10 ± 0.03

Table 1. Mean and standard deviation values for *loudness* and *roughness* on each section.

Permeability - Ligeti's concept of *permeability* is linked to the audio descriptors of *spectral irregularity* and *spectral entropy*. By observing the two curves at the lower half of Figure 1, we can also observe a distinct profile within each one of the sections of the piece.

In the first section, a regular fluctuation of the values is observed in both descriptors, but *entropy* displays a lower range of variation relative to the mean ($\sigma/\mu = 0.64$ for *irregularity* and $\sigma/\mu = 0.31$ for *entropy*, according to the values in Table 1). In the second section, we can observe an ascending pattern in both features, similarly to what was observed for *loudness* and *roughness*, with increasing spikes in the *spectral entropy* profile. The same observation can be made here for the relative variation of both features, with $\sigma/\mu = 0.34$ for *irregularity* and $\sigma/\mu = 0.20$ for *entropy*. Finally, the appendix displays once again the lowest values in both descriptors, as observed with *loudness* and *roughness*, with smaller relative *entropy* variation ($\sigma/\mu = 0.30$) with respect to irregularity ($\sigma/\mu = 0.66$).

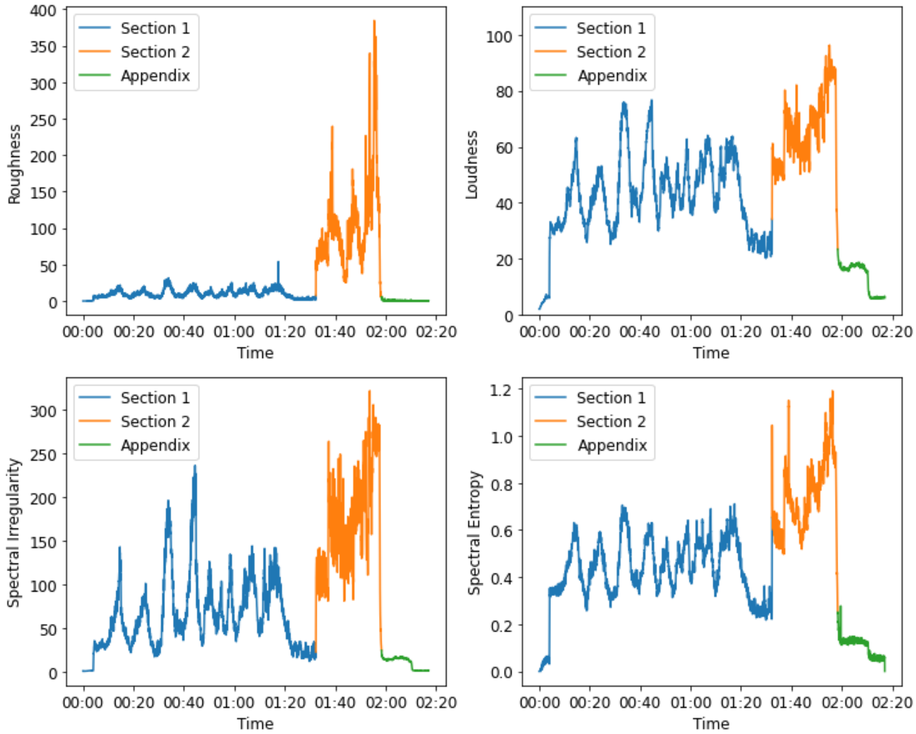

Fig. 1. *Roughness* (upper left), *Loudness* (upper right), *Spectral Irregularity* (lower left) and *Spectral Entropy* (lower right) for the 3 sections of the piece.

By observing all descriptors taken together, we see that the three sections of the piece have very different behaviors from the perspective of their perceptual features. The psychoacoustic difference between the sections is illustrated in the first plot of Figure 2, which represents the relationship between *loudness* and *roughness*, and in the correspondence between *spectral irregularity* and *spectral entropy*, shown in the second plot of Figure 2. In both graphs, the spatial placement of the three section clusters, as well as their geometrical arrangement, make the exploration of *timbre of movement* and *permeability* relatively explicit, allowing us to observe a link between the formal division of the composition and the different perceptual feature aspects of the sound material.

Section 1 has a focus on the global behavior of the musical texture in terms of *timbre of movement*, with a high variation of *permeability*. Section 2 emphasizes *timbre of movement* with a focus on the *microtime* behavior, while at the same time reaching the highest levels of *permeability*. The appendix displays a low level of activity in terms of both *timbre of movement* and *permeability*. It is interesting to observe that, with respect to the first section, we see the blue cluster lying horizontally on the scatter plot, where the large variations in *loudness* emphasize the global dynamic perception. In contrast, the second section (orange) corresponds to a highly scattered cluster in both *roughness* and *loudness* axes, but concentrating on high values of *loudness*, thus bringing the *mi-*

crotime behavior (variation of *roughness*) to the forefront. In terms of *permeability*, we

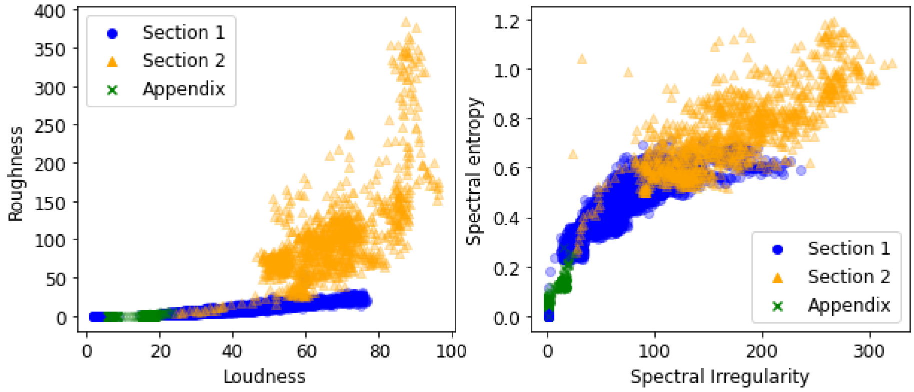

Fig. 2. Scatter plot with the *loudness* (x-axis) and *roughness* (y-axis) values (left). Scatter plot with the *spectral irregularity* (x-axis) and *spectral entropy* (y-axis) values (right)

can observe in Figure 2 that the *spectral irregularity* and *spectral entropy* fluctuations in all sections are highly correlated, producing a log-like, quasi-diagonal shape in the scatter plot, which correspond to constant changes of pitch perception in the musical texture. This might be associated with the harmonic technique of *blurring* [8, p. 122], used by Ligeti to manipulate the musical texture. Especially in the second section (orange), the higher values of *loudness* and the large variation of the spectral descriptors obliterate the perception of individual events, turning our attention to the mass behavior of the composition. Finally, it is interesting to notice that the low level of all descriptors in the third part (green) could be the reason why Vitale [33] described this section as an appendix of the piece.

5 Conclusion

In this paper we presented a methodology for the musical analysis of *sound mass* compositions, based on audio descriptors associated with Ligeti's concepts of *timbre of movement* and *permeability*. In terms of the musicological interest in audio analysis techniques focused on *sound mass* composition, the proposed method reinforces the idea that the perceptual features associated with the performance of a musical work bring important elements that help understanding the formal development of a work, without reducing the importance of symbolic analyses based on the musical score. By analyzing the psychoacoustic features of each section of this particular piece, we may argue that the most important perceptual characteristics of the work do not depend heavily on specific choice of pitches, rhythms or harmonies, but are highly anchored on the perceptual qualities of the *sound masses*. Also, audio descriptors could expand the *gradual process* approach [32], enriching the symbolic analysis with performative characteristics of the piece.

Future work may focus on investigating other timbre-related psychoacoustic descriptors in the context of the proposed analysis, to verify whether they contribute to a better understanding of the perception of similarity of *sound masses* [22]. The study of other audio descriptors in the context of *sound mass music* could also foment applications in the field of creative processes, particularly in computer-aided composition and musical modeling. Exploration of perceptual features of a musical work through comparative analysis of different recordings of the same piece is also an interesting avenue for future work. It would be useful to investigate how the interpretative choices in different performances could reveal the invariant properties of a musical work [35], as expressed in the score. Finally, musical analysis with audio descriptors might help in empirical studies with musical excerpts [12], offering exploratory ways to represent perception attributes of non-expert listeners.

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