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Modification of the Perception of Musical Timbre by Underwater Loudspeaker Broadcasting

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ABSTRACT

The modification of the musical timbre and its perception, during the listening of a music diffused by underwater loudspeaker, is interesting to quantify for purposes of recommendations to underwater composers. This perception is influenced by the nature of the listening with ears immersed in water, thus by the aquatic acoustic channel on diffused frequency content. The additional modification of perception, related to listening by bone conduction which is specific to the underwater listening, is not quantified here. *Everybody Here Wants You by Jeff Buckley* (1998, Rock) was broadcasted in a swimming pool, and the acquisition was made by an hydrophone according to a precise protocol. The segmentation and time-frequency analysis has been made according to 6 zones of interest (drums, hi-hat,...).
The objective quantification of the timbre modification is done via the 8 perceptual models of the *Timbral Explorer* (European project Audio Commons -2019). In our experimentation, the sound diffused in water is less reverberant, sharper and rougher than in the air. Recommendations to underwater composers, according to the frequency bands of the musical instruments are possible.
For example, the depth -the most searched timbre attribute on Freesound- decreases; it is possible to modify the spectral balance by boosting the low frequencies to have a deeper sound.

Keywords: *underwater music, musical timbre, perceptual models.*

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1. INTRODUCTION

This study is part of a cooperation between the Tunisian startup spinoff of University of Tunis El Manar dB.Sense[2], and the French startup Ocean'sArise[3] (O.A). O.A designs aquatic loudspeakers that can be used in sports coaching, artistic swimming, underwater music therapy and aquatic concerts. Sounds would be broadcasted to guide, give instructions, relax or simply be listened and enjoyed - in an audio spectrum from 40 Hz to 12 KHz, making these speakers distinguishable by their bandwidth and especially in the low frequencies.
O.A hypothesized about the enveloping and relaxing aspect of such listening. In addition, the French company is interested in the diffusion of underwater music. It collaborates with the underwater composer Olivier Florio who composes, among other things, music for underwater concerts. Studies were conducted earlier by another composer, Michel Redolfi, in order to explore the perception of timbre in underwater listening, a line of research that aroused our curiosity and suggested the study of musical timbre [11]. The availability of the *Timbral Explorer* tool, from the European project Audio Commons, which allows to calculate timbre attributes from an audio sample, motivated us further. These attributes were chosen according to their popularity among users of the Freesound[4] website.

In this study, first we present perception of musical timbre through perceptual models of Audio Commons,

[2] http://dbsense.tn/index.html
[3] https://oceansarise.fr/
[4] https://freesound.org/

then we present our experimentation and audio processing and results an discussion.

2. PERCEPTION OF MUSICAL TIMBRE: PERCEPTUAL MODELS OF AUDIO COMMONS

The attributes related to the timbre are numerous. The goal here is not to make an exhaustive synthesis of the timbre attributes. There are many theoretical works on the subject (let us quote for example [1-3]).
The timbre is one of the four fundamental parameters that describe a sound, with the pitch, intensity and duration [1].
Some define timbre by negation of these last three characteristics [4], others by what allows us to identify a musical instrument [5]. Let us simply remember that timbre is "*an analytical domain shaped by the spectral, temporal and spectro-temporal elements of a sound signal (i.e. frequency amplitude and their evolution in time) as well as by culture and history*." [4].

Many theoretical studies have been conducted on the design of objective indicators of timbre like the work of Vassilakis [6] on the analysis of the roughness of audio signals, the work of Fastl and Zwicker [7] which establishes models to calculate the sharpness and roughness and the work of Shin [8] to calculate the booming. MIRToolbox [9], developed as part of the European project *Tuning the Brain for Music*, provides tools to extract musical features from audio files. It is widely used by the community of musicians and audio signal processors.
The Timbral Explorer, on which we will rely in the following, offers users the possibility to access sounds according to their timbral properties. It has also the specificity to automatically characterize sounds according to their non-musical characteristics.
We have chosen to use the perceptual models of the *Timbral Explorer* for several reasons:
- **Reliable source** since it is issued from a European project which gathers partners as *Music Technology Group*, *Institute of Sound Recording*, *Centre for Digital Music*, *Centre for Vision, Speech and Signal Processing*, *Surrey Business School*, *Jamendo*, *AudioGaming* and *Waves*.
- **Offers 8 perceptual models** to characterize the timbre of a sound, and details the whole procedure followed to develop these models in deliverables.
- **Offers the source codes** of the perceptual models on Github.

These 8 perceptual models are the following : brightness, depth, warmth, roughness, sharpness, reverb, hardness and boominess.

3. EXPERIMENTATION AND AUDIO PROCESSING

3.1 EXPERIMENTATION

The data are acquired with a hydrophone immersed in the water which captures the sound emitted by a speaker also immersed in the water. The characteristics of the Ocean'sArise underwater speaker are as follows:
- Bandwidth: from 40 Hz to 12 kHz at -3dB
- SPL max: 170 dB at 1 m when used at 80 W

The characteristics of the hydrophone are as follows:
- Reference : AS-1
- Linear band : from 1 Hz to 100 Khz ± 2 dB
- Dimensions : 12 mm diameter and 40 mm length

The loudspeaker is immersed in the municipal swimming pool of Couloisy (France) whose dimensions are Length : 25 m- Width : 12.5 m - Depth : 2.80 m

The hydrophone is placed at a depth which allows to hear with the headphones a sound the closest as possible to what the ear hears under water, at the same place. It is the sound acquired by the hydrophone which will be the subject of our analysis.
There were 2 experiments which differ by the position of the hydrophone compared to the loudspeaker.
We analyze here the recordings from experimentation #2.
We analyze the following data:
- An audio recording by hydrophone, of pink noise diffused in the water by the loudspeaker, sampled at 48 kHz in wav format.
- A wav file of the music broadcast, sampled at 44.1 KHz and duration 4'47".
- An audio recording by hydrophone of the music diffused in the water by the speaker, sampled at 44.1 kHz, in wav format and lasting 1'09".

The diffused music is the song of Jeff Buckley *Everybody Here Wants You*, released in 1998 of the genre Rock according to Apple Music. The instruments identified in this piece are: drums, electric guitar, electric bass, “nappes” (a “nappe” in electronic music is a long and not very marked sound which underlines a note or a chord (set of notes) and a male voice.
We define here a sound as *original sound* if it is extracted from the signal of the music diffused by the

loudspeaker. We define this sound as *aquatic sound* if it is extracted from the signal acquired by the hydrophone.

3.2 Audio preprocessing

In the following we prepare the final data that we will use in our analysis:

- a synchronization,
- a segmentation by area of interest,
- a leveling in decibels per zone of interest,

in order to appreciate the frequency distortions induced by the acoustic environment.
For each zone of interest, we will have the original segment and its aquatic correspondent.
The choice of segments to be studied is made on the basis of instrumental content. We will make a balance between:

- Having a minimum of instruments playing simultaneously in the same segment, in order to better discern the effect of the acoustic channel on the playing of different musical instruments. For example, if we have a segment where there is only the guitar, we will be able to interpret the effect of the acoustic channel on the guitar playing better than in a segment where there is guitar, voice and electric bass. Indeed, the superposition of several instruments complicates the analysis and the interpretation. In our experiment only the drums have their own segment, the other segments contain two instruments and more.

- The variety of segments to explore the influence of the underwater environment on different combinations of instruments.

We take the example, in figure 1, of the segment high male voice+drums+guitar in the temporal domain

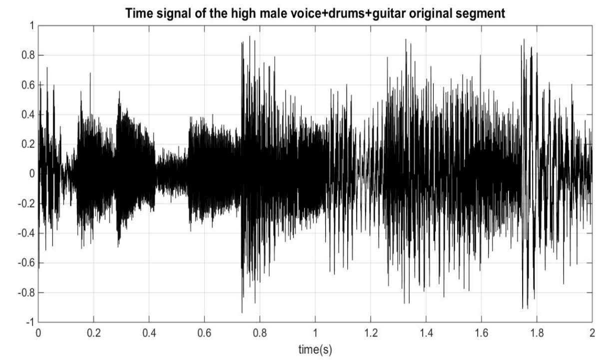

Figure 1. Time signal of the high male voice + drums + guitar segment

4. RESULTS AND DISCUSSION

4.1 Modification of timbre perception

Figure 2 compares the Power Spectral Density (PSD with Welch method estimation) of the original and aquatic *high male voice+drum+guitar segment*:

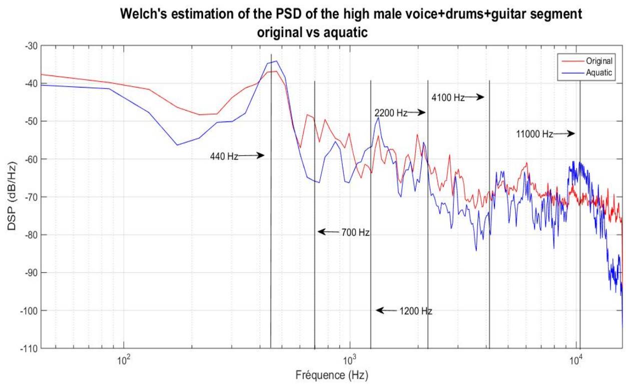

Figure 2. Welch's estimation of the PSD of the high male voice+drums+guitar segment original and aquatic.
The aquatic signal is attenuated around 700 Hz, and in the interval [2200 Hz, 4100 Hz], it is amplified around 1200 Hz, 4500 Hz and 11000 Hz.

As shown in Figure 3, for all the segments included, the perception of hardness tends to decrease, depth tends slightly to decrease, brightness tends to increase and roughness tends slightly to increase, the warmth attribute tends to decrease and the attribute sharpness tends to increase and we can't conclude anything for boominess. As for the attribute reverb attribute, the reverberation is suppressed in water.

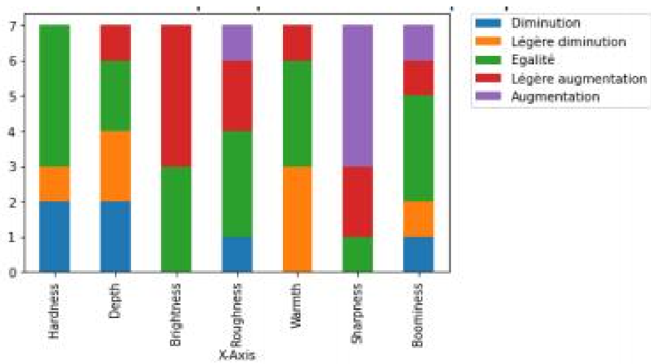

Figure 3. Global modification of the perception of *Everybody Here Wants You by Jeff Buckley* (1998, Rock) broadcasted in the Couloisy swimming pool experiment.

4.2 Discussion: comments in relation to underwater musical composition

Recommendations for underwater composers is possible, by analyzing the frequency bands of about twenty musical instruments [9] in order to see the frequencies around which we have attenuations (2000 Hz and 5500 Hz) and those around which we have amplifications (1200 Hz, 4000 Hz and 10,000 Hz) in the experimental situation tested.

We have thus divided these instruments into 3 classes:

- Class 1: instruments whose timbre will be modified, where all the attenuations and amplifications affect the fundamentals, like the organ whose fundamental frequencies exceeding 10,000 Hz.
- Class 2: instruments whose timbre will be less modified where some amplifications and attenuations affect harmonics, and others affect the fundamentals, such as the piano, violin, female voice, clarinet, oboe, piccolo and flute.
- Class 3: instruments whose timbre will be little modified where only the harmonics are exposed to distortion, such as snare drum, horn, male voice, bassoon, contrabassoon, trombone, trumpet, cello and tuba.

If, on the other hand, a watery timbre is desired, composers would be well advised to use instruments from classes 1 and 2 where the change in timbre would be more perceptible.

5. CONCLUSION

This exploratory study devoted to the modification of the timbre during aquatic listening allowed us to analyze the influence of the environment on the frequency content and the perceived timbre of the music. The comparative time-frequency analyses of the aquatic and original segments, allowed to identify -for a situation of location of the loudspeaker and hydrophone in a specific pool- the frequencies that were amplified or attenuated in the water. This was confirmed by estimating the frequency response of the underwater acoustic channel. These results reinforced the hypothesis that the aquatic timbre differs from the aerial one. We used perceptual models developed in the Audio Commons project to quantify the change in eight timbre attributes.

We found that sound diffused in water was less harsh, less reverberant, sharper and rougher than when diffused in air. We did not conclude anything about the brightness, warmth, depth and boominess attribute.

It would be possible to objectify the change in the induced emotion with indicators such as "miremotion" from MIRToolbox [10] which predicts the emotion following the "Tension Activity Valence" model for the emotions Fear Sad Tender Happy Anger. A library of synthesized sounds evoking the aquatic universe and associated sensations, while taking into consideration timbral properties, could be developed to be exploited by composers. The Ocean'sArise loudspeakers, which are distinguished by their bandwidth of up to 40 Hz in the low frequencies, allow for additional underwater musical listening. It is listening "by the whole body" according to the participants, "by cranial bone conduction" according to the aquatic composer Redolfi [11] and as this has been analyzed more finely in [12], this wrapping sensation is probably a bi-sensorial perception, auditory and vibro-tactile.

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