SONIFYING ECOG SEIZURE DATA WITH OVERTONE MAPPING: A STRATEGY FOR CREATING AUDITORY GESTALT FROM CORRELATED MULTICHANNEL DATA

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ABSTRACT

This paper introduces a mapping method, *overtone mapping*, that projects multichannel time-series data onto a harmonic-series structure. Because of the common-fate effect of the Gestalt principle, correlated signals are perceived as a unity, while uncorrelated signals are perceived as segregated. This method is first examined with sonification of simple, generic data sets. Then overtone mapping is applied to sonification of the ECoG data of an epileptic seizure episode. The relationship between the gestalt formation and the correlation in the data across channels is discussed in detail using a reduced 16 channel data set. Finally, sonification of a 56-channel ECoG data set is provided to demonstrate the advantage of the overtone mapping.

1. INTRODUCTION

We report a method to represent correlation structures of multichannel signals. This method, called *overtone mapping*, projects large-scale, multichannel data onto a harmonic series (a.k.a. an overtone series) of a sound, and the correlated elements across channels are perceived as a fused “auditory gestalt[1].” The benefit of the method is that humans can intuitively perceive the similarity patterns across channels in the data without statistical analyses. We first describe the principle of this method, and then we introduce the application for electrocorticography (ECoG) data during an epileptic seizure episode.

A harmonic series is a commonly found structure in voices and instrumental sounds. We perceive harmonic series as a single, integrated stream of sound, when they share common fate, and their temporal deviations are perceived as deviations in timbre. Using this property, we could present a set of independently measured data channels as a coherent auditory unit when the data share a common fate across channels–i.e., when the data are correlated.

Although this work might seem to be just another example of parametric mapping sonification of brain-wave data, in addition to the previously introduced, sophisticated sonification examples [1, 2, 3], we trust that this work contributes to finding a design-by-principle method for perceptually meaningful sonification. Readers might recall the problems Flowers pointed out in his paper in ICAD2005 [4] as “things we need to know more about.” In this section, he questions the role of timbre in stream segregation, and seeks a method to monitor two or more processes that are co-occurring in real time. We believe this paper answers some of these questions. This is also an example of using timbre as a medium for projecting the complexity of data, as urged in the notable publications [5, 6, 7].

In this paper, we explore the gestalt principle and the effect of overtone mapping by theoretical considerations and sound examples, rather than merely conducting a user-evaluation test. We request that our readers spend some time exploring the sound examples provided online. All of the sound examples that we discuss in this paper are uploaded on this Website:
http://www.tara.tsukuba.ac.jp/%7Eterasawa/ICAD2012/

In the following sections, we first briefly review the common-fate principle in gestalt perception. Then we describe overtone mapping by generic data examples and apply overtone mapping in ECoG data sonification.

2. AUDITORY GESTALT FORMATION AND THE SONIFICATION OF CORRELATED DATA

2.1. Auditory gestalt and its principles

Gestalt perception is the perception of a specific whole or unity, by integrating its parts. Similar to the visual domain, gestalt perception also occurs in the auditory domain. The phenomenon of auditory gestalt is well discussed in “Auditory Scene Analysis” by Bregman [8]. The formation of gestalt perception is described by several principles. Elements such as proximity, symmetry, similarity, continuation, closure, and common fate contribute to the perceptual organization.

2.2. Common fate shared across harmonic series produces a perception of unity

Among those, the common-fate effect was well-investigated in the writing and compositions by John Chowning. He introduced how to form auditory gestalt in terms of the common-fate principle [9, 10, 11]. On a harmonic series of sinusoids, he applied subtle frequency modulations (micro-modulation) at a few different modulation frequencies that mimick vibrato, with some overtones at one vibrato frequency and some other overtones at another vibrato frequency. As a result, the sinusoids that were modulated with the same vibrato frequency became perceived as a unity, and a few voices can exist simultaneously in a stream. In other words,

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[1] In this paper, we use “auditory gestalt” meaning “a perceived auditory unity,” and “Gestalt principle” meaning the grouping law proposed by German Gestalt school of psychology.

the “common fate” in Chowning’s examples is afforded by sharing the same vibrato frequency among harmonic series. Using this technique, he was able to render gradually arising vibrato voices out of a static sinusoidal superposition. This effect is well employed in his pieces *Phoné* (1980-1981), and *Voices* (2005).

2.3. The correlation across channels can function as common fate for an auditory gestalt

Formation of a unity perception by the harmonics sharing common fate provides a good opportunity for data sonification of multichannel, correlated, time-series data. In multichannel time-series data, such as electromyograph (EMG), electroencephalogram (EEG), and electrocorticography (ECoG), the acquired data are often strongly correlated across channels. The similarity analysis, or any other kind of statistical analysis of the correlated yet separately measured time-series data is computationally demanding. Using the common-fate effect, in other words, interpreting the correlation as a common fate, we can easily present the correlated data as a perceived unity, arising out of uncorrelated elements, without applying statistical analysis beforehand.

3. OVERTONE MAPPING WITH GENERIC DATA

In this section, we describe the formation of auditory gestalt by the common-fate effect using generic data and their sonification examples. The sound examples are provided as sounds 1-6 on the Website. Readers are strongly recommended to listen to these sounds to experience the auditory gestalt formation by the common-fate effect.

3.1. Sound 1: Harmonic series with sinusoidal amplitude modulation

This is the reference pattern for the rest of the examples. Figure **??** shows the amplitude pattern for the time course of this sound. The fundamental frequency is 440 Hz, and the sound has eight harmonics (i.e., overtones at integer-multiples of the fundamental frequency). Each of eight harmonics is amplitude modulated with a sinusoidal pattern of a single modulation frequency. Sharing a single modulation pattern, all the harmonics are perceived as unity.

3.2. Sound 2: Static and sinusoidal patterns

In Sound 2, the modulations of the 3rd, 6th, and 7th harmonics are removed as shown in Fig. 2. Now these harmonics with a static pattern are perceptually segregated, forming another unity of static tone. The rest of the harmonics with sinusoidal modulation forms another unity. The degree of segregation is moderate compared with some of the following examples.

3.3. Sound 3: Sinusoidal patterns with two frequencies

In Sound 3, the modulations of the 3rd, 6th, and 7th harmonics are slower, as shown in Fig. 3. These harmonics with the slower modulation pattern are perceived segregated forming a clear unity. The rest of the harmonics with sinusoidal modulation form another unity.

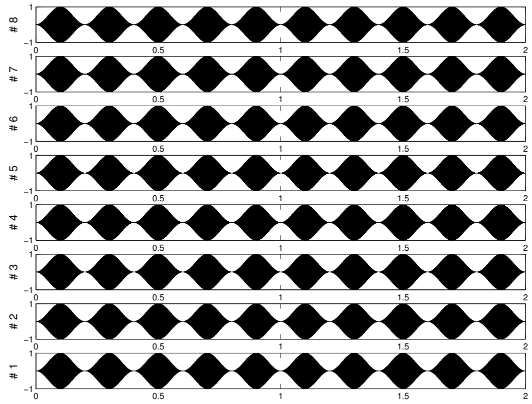

Figure 1: Sound 1. Each row in the figure shows the amplitude pattern over time of each harmonic, from the 1st to the 8th harmonics from the bottom to the top row, respectively. This example has the same sinusoidal amplitude pattern for all the eight harmonics.

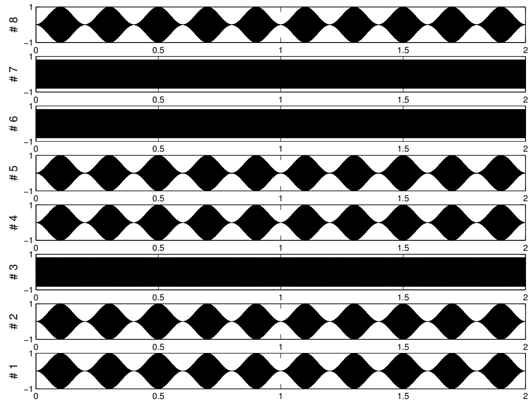

Figure 2: Sound 2. The 3rd, 6th, and 7th harmonics are static without modulation, providing a static tone unity.

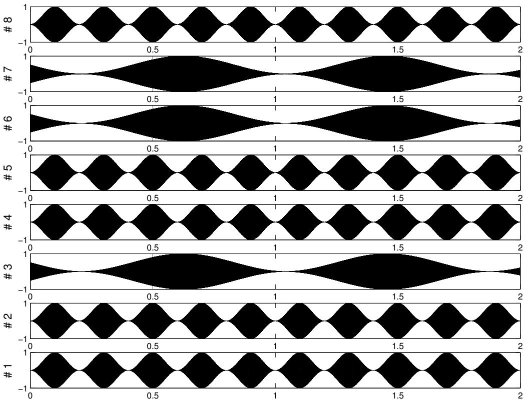

Figure 3: Sound 3. The 3rd, 6th, and 7th harmonics are modulated with a slower modulation frequency.

3.4. Sound 4: Chirp-like and sinusoidal patterns

Sound 4 provides a dynamic transition in the temporal pattern as shown in Fig. 4. The frequency of amplitude modulation at the 3rd, 6th, and 7th harmonics increases over time, forming a chirp-like pattern. When two modulation frequencies (one for 3, 6, 7, and another for the rest) are very distant, the segregation is easier. However, when the two modulation frequencies are crossing, all the harmonics are perceived fusing into a unity.

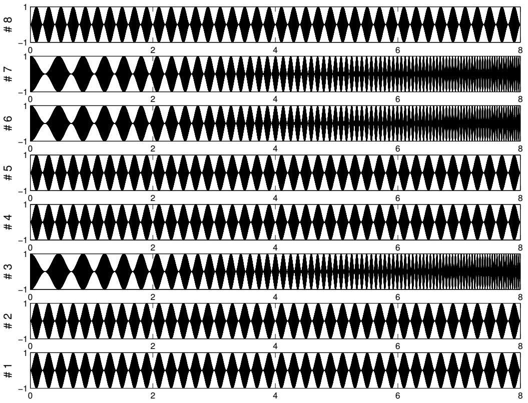

Figure 4: Sound 4: The modulation frequency for the 3rd, 6th, and 7th harmonics increases over time.

3.5. Sound 5: Non-sinusoidal and sinusoidal patterns

So far, we have considered only sinusoidal and static patterns. This example, Sound 5, provides the case that a temporal pattern does not need to be sinusoidal. As shown in Fig. 5, the 3rd, 6th, and 7th harmonics now share a pattern of decaying amplitude. When we hear this sound, these harmonics are perceived as a quickly decaying unity, against the sinusoidally modulated unity of the rest. This segregation is clearly perceived.

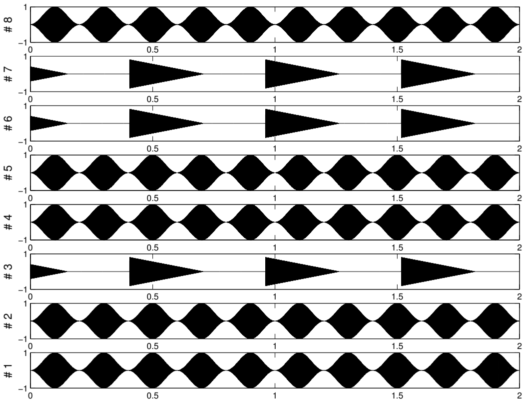

Figure 5: Sound 5: The 3rd, 6th, and 7th harmonics share the decaying-amplitude pattern.

3.6. Sound 6: Sinusoidal patterns with a phase difference

After considering the patterns varying with their duration, it is now worthwhile seeing whether we could create segregation just by changing the phase of the same sinusoidal pattern. Sound 6 provides such an example: the 3rd, 6th, and 7th harmonics are now presented with a $\pi/4$ phase difference from the rest of the harmonics, as shown in Fig. 6. The segregation is ambiguous yet noticeable. As the phase difference reaches the opposite (a difference of π), the segregation becomes slightly clearer. However the unities that differ only by their phase are easily confused.

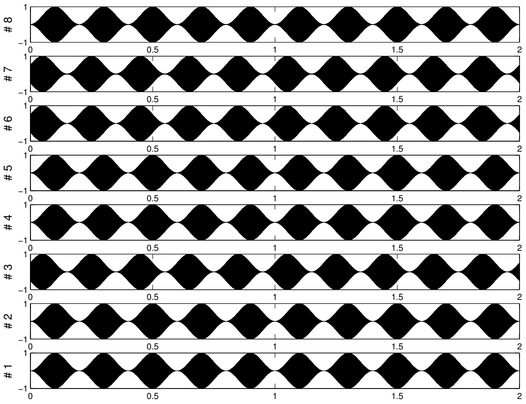

Figure 6: Sound 6: The 3rd, 6th, and 7th harmonics differ only by their phase from the rest of the harmonics.

3.7. Discussion of the generic data examples

In this section, we demonstrated the principle of auditory gestalt formation by common fate with the sonification of simple, generic temporal patterns. The more the temporal patterns differ from each other, the clearer the perceptual segregation is. These temporal patterns could be sinusoidal as having shown by Chowning's examples, or they could be non-sinusoidal patterns as provided in Sound 4 and 5 examples, as long as a set of harmonics shares the same common fate. The grouping by phase is noticeable but not prominent.

4. OVERTONE MAPPING APPLIED TO ECOG DATA

4.1. About the ECoG data

In this section, we consider the overtone mapping method applied to a set of ECoG signals. The ECoG measurement was done as a part of clinical procedure by Josef Parvizi at Stanford University Hospital, under the guidance of Stanford Institutional Review Board. The patient was personally consulted about the project and gave full consent. The original signals were measured with 56 channels, and the measurement lasted for many days. In this discussion, we focus on the excerpt of only 10 s. This excerpt captures a very interesting moment in the epileptic seizure episode, in which multiple channels show the mixture of coherent and non-coherent neural activities.

This excerpt for 56 channels is plotted in Fig. 7. These 56 channels show complex correlation patterns, to which we will return at the end of this section. However, in order to address the relationship between the correlation and common fate effect, 56 channels are just too many. Therefore, we decided to select some prominent channels out of 56. Figure 8 shows a stem plot of the mean absolute amplitude of the 56-channel data. As you can see from the figure, some of the signals are stronger than others, and we selected the 16 strongest mean-absolute-amplitude channels, assuming those strong channels carry more meaningful information with less measurement noise.

4.2. Sonification of ECoG data

The sonification of the 16-channel excerpt data was done using the following procedure.

1. The fundamental frequency was set to 180 Hz.
2. Harmonics of 16 sinusoids (up to the 16th harmonics) were created.
3. Each harmonic was amplitude-modulated by each channel: the 1st harmonic is modulated with channel 1, the 2nd with channel 2, and so on.
4. All of the harmonics were summed, creating a single audio signal.
5. The audio signal was linearly scaled with its maximum value, so that the scaled signal could fit within the .wav file dynamic range.

The 16-channel ECoG sonification is available as "ECoG Sound 1" on the Website.

Listening to the sonified sound, we notice some clear patterns existing within the dynamically transitioning harmonic series, although the mapping was decided blindly without signal analysis.

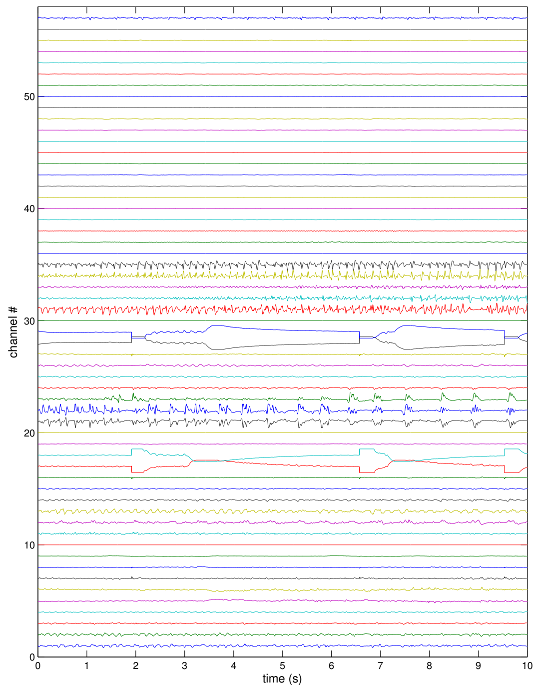

Figure 7: Plot of 56-channel ECoG data for 10 s. Each line shows the signal for each channel, from the bottom to the top showing channels 1 to 56, respectively.

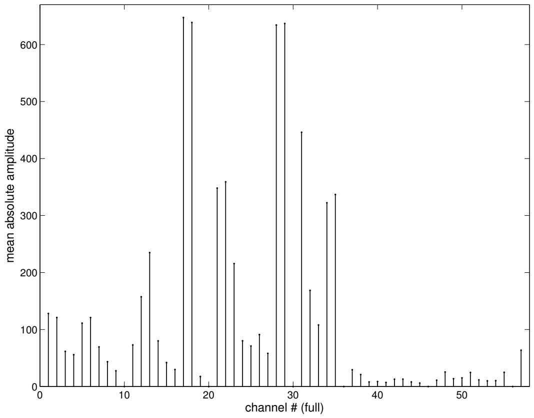

Figure 8: Mean absolute amplitudes of channels 1-56. 16 channels with strong amplitudes were selected for the following discussion.

Table 1: Groups of Correlated Signals

Group	Channels
1	1, 2, 3, 4, 5, 8, 9, 10
2	6, 7, 11, 12
3	13, 14, 15, 16

4.3. Discussion on the ECoG data sonification

When we listen to the 16-channel ECoG data sonification, we notice that there are a few recognizable gestalts, which can be identified with correlation analysis. Figure 9 shows the correlation matrix of 16 channel signals on 16 $\times$16 square color tiles. Each square at (n, m) position represents the value of correlation between the signals at channel n and channel m. By viewing this figure, we could find a few islands of more correlation–namely groups 1, 2 and 3–of the channels listed in Table **??**.

By creating subset-tones of the sonification, we can verify the formation of auditory gestalt. This could be done by replacing the step 4 of the procedure introduced in Section 4.2. Instead of summing all of the harmonics, we now sum only the harmonics that correspond to each group. Figure 10 shows the wave plot of each subset-tone for groups 1, 2, and 3. These subset-tones can be heard as ECoG sound 2-4 on the Website.

As verified in the waveform plot and sound examples, each group of correlated signals clearly forms an auditory gestalt, which is easily recognized. The recognizable patterns in the 16-channel sonification were the auditory unities arising from the correlated signal patterns.

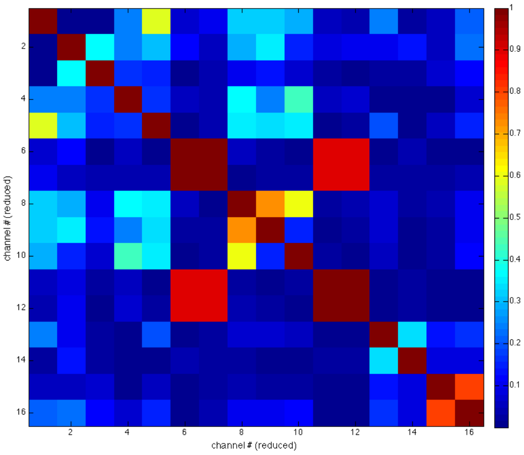

Figure 9: Correlation matrix of the selected 16-channel signals.

4.4. Demo: 56-channel ECoG data sonification

Finally, we want to introduce the full-data example. However, analyzing the similarity in 56-channel signals becomes increasingly challenging. Figure 11 shows the correlation matrix in the same way as Fig. 9, but its correlation patterns are not easily recognizable. However, when we listen to the sonification of the 56 channels (fundamental frequency: 120 Hz; number of harmonics: 56), we can hear a handful of patterns with rich textures arising from the broad spectral components, in the same way as its 16-channel version. The 56-channel sound is provided as “ECoG Sound 5” on the Website.

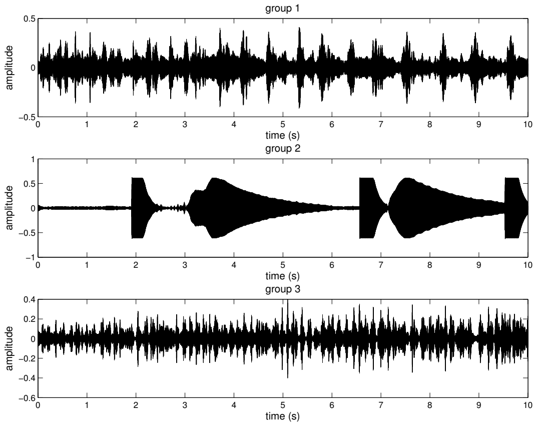

Figure 10: Waveform plot of subset-tones of sonification: Group 1 (top), group 2 (middle), and group 3 (bottom).

The visual representation of the correlation is not trivial, but the auditory representation of the correlation by common fate effect is more recognizable.

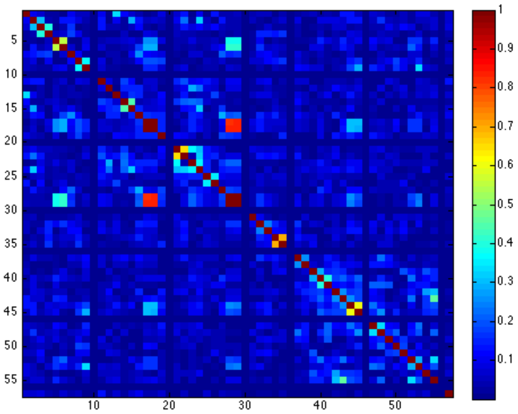

Figure 11: Correlation matrix of the full 56-channel signals.

5. CONCLUSION AND FUTURE WORK

In this paper, we discussed the formation of auditory gestalt by the common-fate principle. With the generic data sonification, we demonstrated that two distinct temporal patterns can be mapped to amplitudes of harmonic series, and that this mapping can provide a auditory segregation. The degree of segregation–i.e. how clearly the auditory gestalts can be perceptually segregated–depends on the degree of similarity between the two temporal patterns. The temporal pattern could take any shape other than sinusoids, as long as it holds a distinct temporal pattern. In the later section of the paper, we introduced another example that applied the same mapping to real 56-channel ECoG data. With the reduced 16-channel version, we could see the clear correspondence between the data correlation and auditory gestalt formation by overtone mapping. Furthermore, the 56-channel version serves as an example that auditory gestalt formation is much easier and simpler than statistical analysis of the data similarity across many channels. The advantage of overtone mapping is that our auditory perception can easily judge the similarity of the signals across channels.

In this paper, we presented the gestalt formation by overtone mapping by conceptual and theoretical considerations and by sound examples. Quantitative formalization of this technique remains as a future consideration. Overtone mapping seems to be a useful approach not only for ECoG signals but also for EEG and EMG signals. Investigating the applications for these, and other types of signals would be desirable in the future. Finally, while this paper describes the auditory gestalt formation using the common-fate principle, another paper by the first author on the sonification of the genetically modified *C. Elegans* [12] provides an example for the gestalt formation by proximity principle. Investigating the sonification according to the rest of the principles (i.e., symmetry, similarity, continuation, and closure) will enable further theorization of the auditory gestalt formation in data sonification.

6. ACKNOWLEDGMENT

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