Beyond Swayambhu Gandhar: An Analysis of Perceived Tanpura Notes

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Abstract

Tanpura sound has rich harmonic structure leading to the perception of several perceived notes for which there are no corresponding tuned strings. We analyse the spectrogram of tanpura to find harmonic partials which correlate well with the perception of these "swayambhu" notes. From this analysis, we determine the exact shrutis of the perceived tanpura notes.

1 Introduction

Tanpura is a multi stringed instrument used as background drone in Indian classical music performances. Tanpura has a very rich droning sound which waxes and wanes and fills the musical atmosphere with rich texture. In Indian music, tanpura fixes the tonic Madhya Saptak (middle octave) Sa note, denoted by Sa1. All the other notes are defined and sung with reference to this tonic Sa1.[1] It is widely held that the tanpura sets the harmonic background in context of which the melody evolves.

Musicians claim existence of excellent consonance between the notes used in raags in Indian music and the tanpura sound. Students of vocal music are routinely advised to practice singing with tanpura which helps in purifying their ability to produce correct "shrutis" (micro-tonal note positions) by feeling the consonance between their singing and the tanpura sound.

Tanpura sound has rich harmonic structure leading to the perception of several notes for which there are no corresponding tuned strings. In this paper, we undertake an investigation of perceived tanpura notes using spectral analysis and digital filtering techniques. We investigate two questions.

1. What perceived notes are present in tanpura sound?
2. What are the shruties of these notes? Shruti here is defined as ratio of the pitch of the note to the pitch of the nearest lower Sa.

A typical tanpura has four strings. The four strings are plucked in sequence to form one plucking cycle and this cycle is repeated throughout the

[1] We shall denote the Sa of Mandra Saptak (lower octave) by Sa0, the Sa of Taar Saptak (upper octave) by Sa2 and Sa of Ati-Taar Saptak (extreme-upper octave) by Sa3. Similarly, for other notes e.g. Ga2.

Tuning Name	String1	String2	String3	String4
SaPa	Pa0	Sa1	Sa1	Sa0
SaMa	M0	Sa1	Sa1	Sa0
SaNi	Ni0	Sa1	Sa1	Sa0

Table 1: Various tunings of Tanpura strings

performance. Different tunings are used depending upon the raag being performed.Table 1 gives some standard tunings used with the tanpura.

In this paper, we confine ourselves to the SaPa tuning only. Musicians report that in a well tuned tanpura with SaPa tuning, we can clearly perceive the notes "Taar Gandhar" (note Ga2) and "Taar Pancham" (note Pa2). With trained ears and very well tuned tanpuras it is claimed that one can hear also the notes Rishabh (Re) and Nishad (Ni). Moreover, these notes appear and disappear at well defined positions within the plucking cycle. The most prominent of these perceived notes is the note Ga2 which has been termed as *Swayambhu Gandhar*.

The associated soundfile tanpura2.wav, available from the internet [9], gives a recording (of total duration 4.67 sec) of one plucking cycle of tanpura with SaPa tuning. We urge the reader to download and listen to this sound. Attentive listeners will notice that in Tanpura with SaPa tuning, the note Ga2 can be clearly heard towards the end (after about 3.4 sec in our sound file) of the tanpura plucking cycle. With more concentration, we can also hear note Pa2 at the beginning of the plucking cycle. We note that these perceived notes are not due to some resonant peaks within the instrument as these effects can be achieved within the full range of re-tuning of the instrument and even across different tanpuras.

In the SaPa tuning of tanpura, one hears notes as outlined above. Since no strings are tuned to the notes Ga2, Pa2, Re and Ni we shall term these as *perceived notes*. In literature, the term "swayambhu" has been used. Notes Pa0, Sa1, Sa0 will be termed as *plucked notes*. Musicians are unclear about the perception of notes such as Ma, Dha in tanpura with SaPa tuning, and no clear perceptual findings are reported to our knowledge. One often stated view is that "all" notes are heard but claimants of this view fail to give precise answer to the question of when in the plucking cycle is each of these notes is heard. More definitive and exhaustive psycho-perceptual experiments are needed to clarify the issue of which notes are heard in tanpura and their time positions in the plucking cycle.

Just as a prism can take coloured light and decompose it into its constituent basic colours, the spectral analysis of musical sound can decompose sound into its basic tones. Musical sound is typically harmonic in nature and its spectrogram consists of harmonically related partials (narrow frequency bands) where all the sound energy is concentrated. See Figures 1 and 2. Spectral analysis of sound can be conveniently carried using modern digital computers. Moreover, it is also possible to retain only some of the components (harmonic partials) of the original sound by masking out the rest by using digital filtering. We can carry out listening experiments with such filtered sound to enhance the perception of some of the contained elements in the original sound.

In this paper, our aim is to do a spectral analysis of the tanpura sound and to identify the spectral components and cues which correlate well with the sensation of the perceived notes. The main technique used is separation of tanpura sound into individual harmonic partials by digital filtering and then listening to the sensation of the perceived note due to these individual partials and also their various combinations. We believe that this simple technique provides a definitive answer to the presence of notes within tanpura sound. Moreover, it is easy to accurately give the shruties of these harmonic partials and hence of the the perceived notes.

Experimental Setup We consider digitized tanpura sound recorded at 16KHz sampling rate which is re-sampled to the more standard 44.1KHz. The sound file editor `MixViews` due to D. Scott [10] is used to carry out and display the 3-D spectrograms of sound signals and to carry out filtering of sound. Mixview provides facilities for filtering the audio using low pass, resonant, comb and elliptical filters. It has a good fft analyser where the results can be plotted as 3-D spectrogram on both linear and log (dB) scale.

Note on Listening to the Sound Files This paper refers to a number of sound files of tanpura sounds and also those obtained by applying digital filters to the original tanpura files. All these files are available on the internet [9]. Each sound file covers only one plucking cycle of tanpura. For proper effect, the sound should be heard repeatedly in a loop for a few cycles. While reading this paper on internet enabled computer, just clicking on the file name (in blue) in the paper should be sufficient to download and start the sound. For example, click on `tanpura2.wav`.

2 The Tanpura Spectrogram

Figure 1 gives the spectrogram of one plucking cycle of tanpura sound recorded in the file `tanpura2.wav`. The spectrogram is calculated with fft window size of 2048 samples. The x axis is frequency and the y-axis is time measured in frame numbers. The window of 2048 samples is shifted by 800 samples to give a new frame for successive fft calculations. The z axis gives the power on a linear (not dB) scale. Figures 2 and 3 give the expanded view of the spectrogram in the frequency range 0-1300 Hzs and 700-2000 Hzs respectively.

From these spectrograms it can be see that tanpura has a very rich harmonic structure. The spectrum has very regularly occurring *bands of spectral peaks* which sustain for long periods. Each such band will be called a partial. Energy is concentrated only in harmonically related partials clearly visible upto about 5KHz on the linear scale. Partials show multiple excitation and decay phases within one plucking cycle.

We observe that the harmonic partials occur at multiples of frequencies 103 and 155; and about 50 such partials can be clearly seen. We shall call 103 Hz as the fundamental frequency for our analysis and denote it as Sa0. We shall denote the frequency 155 Hz as note Pa0. The most prominent partials are at frequencies 620 and 515 Hzs. Interestingly, the partial at 515 Hzs appears at frame 735 (i.e. at time 3.4 seconds) and sustains with slow decay well into the next cycle. From the time of its occurrence, we conjectured that it correlates

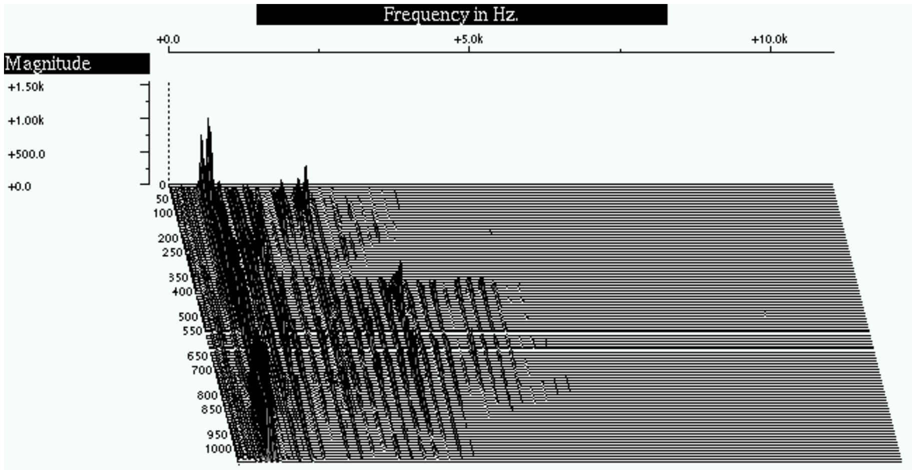

Figure 1: 3D spectrogram of one cycle of tanpura plucking

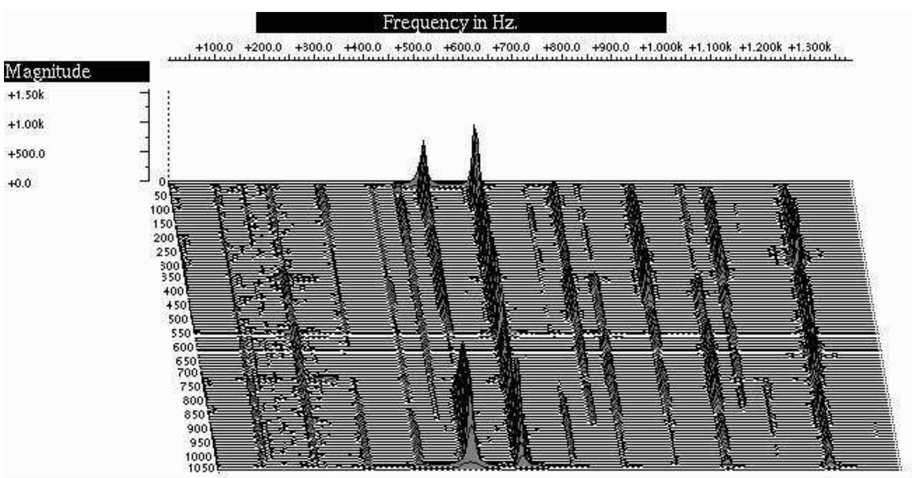

Figure 2: Lower Section of the spectrogram: one cycle of tanpura plucking

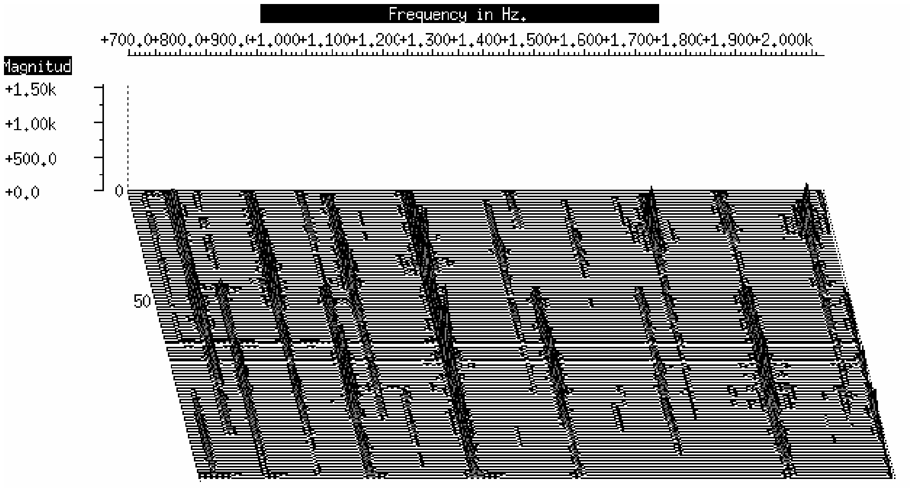

Figure 3: Middle Section of the spectrogram: one cycle of tanpura plucking

well with the perception of the Swayambhu Gandhar, i.e. Ga2 note. We will verify this further in the paper.

Numbering the Harmonics The harmonic partials in the tanpura spectrogram occur at frequencies which are multiples of 103Hz (Sa0) or 155Hz (Pa0). For convenience, we number the partials based on which multiple of 103Hz it is rounding it to the nearest multiple of 0.5. This justified as in principle note Pa is (assumed to be) tuned to ratio (3/2) of Sa and the physics of vibrating strings dictates that harmonic partials occur at multiples of the frequency of Sa or Pa strings of the tanpura. Thus, the partial around frequency 515 will be called the 5th harmonic, that around frequency 420Hz will be called the 4th harmonic where as the partial around 460 Hz will be called 4.5th harmonic. All the harmonic numbers are multiples of either 1 or 1.5.

3 Listening to the Spectral Components

In order to identify the effect of various harmonic components on the perception of tanpura notes, we digitally filter the sound with elliptical band pass filter with sharp roll off (10Hz) and we listen to the resulting sounds. The findings are reported below.

- **Unfiltered Sound** (Sound file `tanpura2.wav`). This file contains one cycle of tanpura plucking. All the other sounds below are obtained by digitally filtering this file.
- **Band 1280-8000Hz** (Sound file `tanpuraHP1280.wav`).
  All the harmonics upto 1280 Hzs are removed. In spite of this, the perceived tuning (or the low/virtual pitch) of the tanpura does not change. Only the timber of the sound is felt as changed. The Jawari effect is prominently retained. The perceived Notes Ga2 and Pa2 are absent.

- **Band 50-1280Hz** (Sound file `tanpuraLP1280.wav`).
All harmonics above 1280Hz are missing. The Jawari effect is significantly muted. Perceived notes Ga2, Pa2 are prominent.

- **Band 1620-8000Hz** (Sound file `tanpuraHP1620.wav`).
All the harmonics upto 1620 Hzs are removed. In spite of this, the perceived tuning (low pitch) of the tanpura does not change. Only the timber of the sound is felt as changed. The Jawari effect is prominently retained. The perceived Notes Ga2 and Pa2 are absent. However, strangely, there is an impression of note Re1.

- **Band 50-1620Hz** (Sound file `tanpuraLP1620.wav`).
All harmonics above 1620Hz are missing. The Jawari effect is significantly muted. Perceived notes Ga2, Pa2 are prominent.

- **Band 650-8000Hz** (Sound file `tanpuraHP650.wav`).
Plucked notes Pa0, Sa1 are heard as before. There is a mild perception of note Ni2 at the beginning of the plucking cycle.

- **Band 50-650Hz** (Sound file `tanpuraLP650.wav`).
Perceived notes Ga2 and Pa2 are prominent. There is a mild short perception of note Re2 at the end of the plucking cycle after Ga2.

- **Band 570-8000Hz** (Sound file `tanpuraHP570.wav`).
Plucked notes Pa0, Sa1 are heard clearly. The perceived note Pa2 can be heard clearly, especially towards the end of the plucking cycle. However, the perceived note Ga2 is absent.

- **Band 50-570Hz** (Sound file `tanpuraLP570.wav`).
Perceived notes Ga2 is very prominent and perceived note Re2 is also clearly heard. The original plucked notes Sa0,Sa1 and Pa1 are not heard.

- **Band 450-8000** (Sound file `tanpuraHP450.wav`).
Apart from Ga2 and Pa2, the note Shudda Rishabh Re2 is heard.

- **Band 50-450** (Sound file `tanpuraLP450.wav`).
Only very muted Sa1 is heard. Thus, most of the content of tanpura sound is above 450Hz.

- **Band 490-640** (Sound file `tanpuraBND490-640.wav`).
Only Notes Ga2 and Pa2 are clearly heard. Plucked notes Pa1, Sa1, Sa0 are muted.

- **Band 400-690** (Sound file `tanpuraBND400-690.wav`).
Very interesting behaviour is observed. There is a definite sequence containing multiple notes Re2, Ga2, Pa2, Sa2. These occur in some well organized sequence.

- **Band 400-1600** (Sound file `tanpuraBND400-1600.wav`).
Various perceived notes Re2, Ga2, Pa2 and Ni2 can be heard with repeated listening.

Harmonic	Freq	Note	Power	Sound File (click to listen)
4	412	Sa2	Weak	tanpuraonly412.wav.
4.5	460	Re2	Weak	tanpuraonly460.wav.
5	515	Ga2	Strong	tanpuraonly515.wav.
6	620	Pa2	Strong	tanpuraonly620.wav.
7	720	Ni-Ko2	Very Very weak	tanpuraonly720.wav.
7.5	760	Ni2 Shuddha	Weak	tanpuraonly770.wav.
8	815	Sa3	weaker	tanpuraonly815.wav.
9	930	Re3	Moderate	tanpuraonly930.wav.
10	1030	Ga3	Weak	tanpuraonly1030.wav.
10.5	1090	Ma3	Weak	tanpuraonly1090.wav.
12	1240	Pa3	Weak	tanpuraonly1240.wav.
13.5	1390	Dha3	Very Weak	tanpuraonly1390.wav.
14	1450	Ni-Ko3	Weak	tanpuraonly1450.wav.
all				tanpura2.wav.

Table 2: Harmonic partials and perceived notes

The above observations strongly direct us to conclude that Harmonic partial at 515 Hzs (the 5th Harmonic of Sa0) leads to the perception of note Ga2. The partial at 620Hzs (the 6th Harmonic of Sa0) strongly correlates with the perception of the note Pa2. At this point, we still need to identify the spectral cues for the notes Re2 and Ni2 which were heard above. This is investigated below.

Listening to Individual Partials We now consider the contribution of each harmonic partial to the perceived notes. In order to determine this, we apply a sharp bandpass filter of bandwidth 30Hz and Roll-off 10Hz centered around each partial. We do this for harmonics upto harmonic numbered 15, i.e. all harmonics below Sa4. We listen to the filtered sound of each harmonic partial and record which musical note is perceived by by the listener. The following Table 3 records the results of this note perception for each harmonic partial sound.

For reader's convenience, in the table, we also give the associated filtered sound files. The file for partial at N Hzs is called `tanpuraonlyN.wav`, e.g. `tanpuraonly515.wav`. We urge the listener to hear these sound files and to convince themselves of our note perception findings. For this, the readers should first hear the full tanpura sound (in file `tanpura2.wav`) and then listen to these partials which may be looped (repeated) a few times to get a more distinct impression.

A significant finding about the tanpura spectrum in this context is that the 7th harmonic of Sa0 is very weak and the odd harmonics above this i.e. the 11th, 13th, 15th, 17th harmonics are practically absent. It remains to be verified if this finding also holds for other good quality tanpura recordings with Sa-Pa tuning.

4 Conclusions and Discussion

We have carried out a spectral analysis of tanpura sound to determine which harmonic partials correspond to which perceived notes in the tanpura sound. Our experiment shows that the rich harmonic structure of tanpura sound indeed leads to the perception of several notes as the musicians have claimed.

Many of these perceived notes are in taar (2nd) or ati-taar (3rd) octave. In particular, with the SaPa tuning we claim to have identified notes Ga, Pa and Ni in Taar Saptak and note Re, Ga, Ma, Pa in Ati-taar saptak. We also found a very very weak presence of Ni-KO in tar (2nd) saptak and very weak presence of notes Ni-Ko and Dha in Ati- (3rd) saptak. In particular, any perception of vikrit notes other than Ni-Ko seem absent.

The other findings are that tanpura sound is surprisingly robust to the loss of lower harmonics. Even when first 15 harmonics are removes the sound retains its (so called virtual or low) pitch and the tuning of the tanpura does not appear to change. The harmonics between 5 to 15 seem to lead to most of the perceived notes whereas Jawari effect seems to be mostly due to harmonics higher than the 15th.

Since, we associate perceived notes with individual harmonics, it is easy to compute their exact shruties. The ratio of the *harmonic number* of a harmonic partial with the harmonic number of nearest lower Sa gives the exact shruti of the perceived note corresponding to that partial. These ratios are listed in the Table 4 below. Obviously, these turn out to be ratios with small integer values as numerator and denominators. The physics of vibrating strings dictates that the actual rations of the frequency of a harmonic partial with the frequency of the nearest lower sa must also be the same as the ratios of their harmonic numbers[2]. Thus, our values are precise.

It should be noted that in the Table 4, *we have only determined the shrutis (intervals) of perceived tanpura notes.* There is no a priori guarantee that these are same as the shrutis used in the melodies of Indian music. There has been much debate about notes, scales and shruti intervals in Indian music. Tradition fixes the number of shrutis at 22 which even have names [8] (pp. 29). Music literature contains several mathematical approaches which derive (different) tables of 22 shruti intervals (ratios) purely by theoretical arguments. (See [2] for some candidate tables.) To resolve their differences, some experimental analysis of sound signals has also been undertaken. Among others, Datta *et al* [2], Sahasrabuddhe *et al* [7] and Bhave [1] have recently carried out a series of experiments to try to measure the shruties used in vocal singing in Hindustani Music. Some authors have argued that in practice the contemporary Indian music is based on 12 notes roughly lying around the equally tempered scale and precise 22 shruti intervals are not really in use [5]. Yet another viewpoint is that shrutis do not refer to intervals but refer to shapes within pitch graphs [12]. The proceedings of the recent FRSM 2004 symposium with over 4 papers with diverse opinions on this issue provide an interesting reading in this respect [2, 12, 6, 7].

One viewpoint often stated in literature is the following. Since it is widely held that for correct intonation of notes the musician must seek consonance

[2]This assumes that the Pa0 string is tuned to frequency 3/2 times the frequency of Sa0 as is widely accepted. Note that FFT based fourier analysis can identify the frequencies of spectral peaks with only limited precision.

Harmonic	Note	Ratio	Strength
4	Sa2	1/1	
4.5	Re2	9/8	
5	Ga2	5/4	
6	Pa2	3/2	
7	Ni-Ko2	7/4	
7.5	Ni2	15/8	
8	Sa3	1	
9	Re3	9/8	
10	Ga3	5/4	
10.5	Ma3	21/16	
11	-	-	Absent
12	Pa3	3/2	
13	-	-	Absent
13.5	Dha3	27/16	Very Weak
14	Ni-Ko3	7/4	Weak

Table 3: Perceived Notes and Their Shrutis in SaPa Tuned Tanpura

with the tanpura sound, *the perceived tanpura notes can be deemed to define correct note positions*. The consequences of accepting this thesis are far reaching. It definitively establishes that the scales used in Indian music, at least in principle, are indeed harmonic as has been widely accepted. This is because the harmonic partials of a plucked string of tanpura occur in precise simple mathematical ratios with respect to the fundamental frequency (see Helmholtz [4] for a classical elaboration of this argument). Secondly, we must accept the above tanpura based shrutis of perceived notes over those proposed in the literature. An examination various Shruti tables as reported in a recent paper by Datta *et al* [2] shows that our tanpura shrutis do not fully agree with any one table (e.g. that of Deva or Bhatkhande) although most ratios do occur in part in different tables.

Theories identifying swayambhu notes with harmonic partials and then determining their shrutis are not new. Indeed, the fact that "the fifth harmonic of Sa gives rise to Swayambhu Gandhar" seems to be generally known to many musicologists and scientists. However, this knowledge is much less precise when going to notes beyond the Swayambhu Gandhar. What our analysis achieves is to carry out a definitive experimental evaluation of the perceptions of notes due to various harmonics and their combinations. The results can be confirmed by the reader by listening to the sound files made available with this paper.

The work reported in this paper is limited in many ways. The work needs to be extended to other tanpura tunings such as the SaMa and SaNi tunings. Also, the work is based on exhaustive analysis of a single tanpura sound. It remains to be confirmed that the results carry over to other tanpura samples too. The effect of tanpura quality and tuning accuracy on these findings need to be studied. For example in some other tanpura recordings we found a stronger presence of 4,7, 9 and 13.5th harmonic and a weaker presence of the 5th harmonic. In such recordings notes Re could be heard much more prominently. Secondly, identifying a perceived note with a single harmonic partial is also questionable. It is likely that a group of harmonic partials combine to enhance the perception of a single note and the presence of such a note may mask out the perception of some other harmonics and notes. There is evidence that human ear is capable of perceiving individual harmonic partials. It is by learning that the brain chooses to identify a collection of partials as a single complex harmonic tone with a pitch and timbre. The temporal dynamics of attack and decay of the harmonics play a role in the perception of a note, its onset and duration. Recent theories of pitch perception of complex musical tones (e.g. Goldstein [3] or Terhardt [13]) suggest that the brain often fits by pattern matching a harmonic series "closest" to the available harmonics in the sound to perceive a single tone (even when some of the component harmonics are missing). This leaves some harmonics unresolved which are then probably grouped again to be perceived as a separate tone. In view of this, it is possible that without acute ear training most listeners may fail to separately identify *all the separate notes* which we have listed in this analysis of a complete tanpura sound. However, the filtered sound files should help in listening to these tones. Finally, a theoretical explanation of the perceptual features of tanpura sound using the existing theories of complex tone perception has not been addressed in literature to our knowledge. Also, the notion of what is "consonant" or "tuneful" with the background tanpura drone requires to be examined by psycho-perceptual experiments.

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