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From Intonation Adjustments to Synchronization of Heart Rate Variability: Singer Interaction in Traditional Georgian Vocal Music

ABSTRACT

This paper is concerned with how singers of Georgian traditional vocal music interact when singing together. Applying a variety of computational methods from audio signal processing and music information retrieval (MIR), we examine three existing corpora of (field) recordings for manifestations of a high degree of mutual coordination of the singers' voices. We find numerous examples of harmonically controlled mutual intonation adjustments on both short and long time scales. Furthermore, we believe that the observed differences in melodic and harmonic scales can also be interpreted as (side) effects of the singers' interaction with the possible goal of achieving harmonic togetherness (or consonance) on the time scale of individual (important) notes. In addition, together with the ensemble Khelkhvavi from Ozurgeti, we conducted an experiment demonstrating the synchronization of singers' heartbeat rates during the performance of the Gurian song *Chven Mshvidoba*. The results of our analysis show that a variety of measurable signs of interaction between singers can be observed and documented in existing corpora of Georgian traditional vocal music. Our experience also shows that relevant information about the synchronization of the bodily functions of singers during performances can nowadays be obtained with reasonable technical and logistical effort even in a 'real world' framework, thereby allowing us to address questions related to the 'ecological validity' of this kind of measurement.

KEYWORDS

Singer Interaction

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Introduction

Traditional Georgian polyphonic singing, which was recognized by UNESCO as a Masterpiece of the Oral and Intangible Heritage of Humanity in 2001 and inscribed on its Representative List in 2008, has fascinated many people for a long time and for different reasons. With the research project *Computational Analysis of Traditional Georgian Vocal Music (GVM)*, funded by the German Research Foundation since 2018, we seek to advance the understanding of traditional Georgian singing by employing computational methods from audio signal processing and music information retrieval (MIR). This paper is concerned with observable signs of singer interaction in traditional Georgian vocal music. More specifically, we explore three existing corpora of (field) recordings for manifestations of high degrees of mutual coordination of singers' voices and/or bodily functions. We make the assumption that the purpose of singer interaction is to achieve some form of 'acting as one entity'[1] or in other words some form of 'togetherness'[2]. The use of the term "entrainment" (Clayton, 2012), which at first glance seems to lend itself to the description of the phenomenon of singer interaction as well, seems on closer inspection to be too narrow in the present context, since we are not only interested in temporal coordination, for which the term 'entrainment' is commonly used, but also in harmonic coordination and its consequences. This notwithstanding, our study has benefited greatly from the concepts developed by Martin Clayton (Clayton, 2012).

The first of the corpora examined, the Erkomaishvili dataset from 1966 (Rosenzweig et al., 2020), is to our knowledge the oldest set of digitized recordings of Georgian chants for which all three time-synchronous voices could be analyzed computationally. Its analysis is covered in a series of papers (Müller et al., 2017; Scherbaum et al., 2017, 2020; Rosenzweig et al., 2019, 2020). It is special in its recording strategy in that master chanter Artem Erkomaishvili (1887 – 1967) was recorded against the playback of his own voice(s). This was done by sequentially recording the three voices using an overdubbing technique, leading to three subsequently recorded temporal segments. The top voice,

[1] A metaphorical image for this 'acting as one entity' is the flocking of birds, when the movement of individual birds becomes affected by the geometrical constraints of the movement of the flock (direction, speed, distance between individual birds). An analogy in polyphonic singing would be the superposition of melodic intentions (which represent the individual birds) and harmonic constraints (which represents the flock).

[2] The topic of achieving 'togetherness' in ensemble performances (in a general context) is currently the topic of a research project hosted at mdw – University of Music and Performing Arts Vienna (https://mdw.ac.at/togetherness/).

which in Georgian chant is also the leading voice, was recorded first (as a solo voice), then played back to him while he was singing the middle voice. Finally, he sang the bass voice against the playback of the superposition of the top and middle voice. This overdubbing technique, which was originally employed only because of the lack of fellow singers, simplifies the task of determining the fundamental frequencies F0 (which for simplicity we will also refer to as pitches) for all voice segments. Details of the processing techniques can be found in Müller, 2015. The synchronized pitch tracks for the individual voices, on the other hand, offer the opportunity to investigate 'asymmetric voice interaction'[3] of one of the last professional master chanters of the last century, opening a unique window onto earlier musical thinking.

The second corpus, which we refer to as the GVM dataset, was collected during extensive ethnomusicological field expeditions to rural Georgia, which the first author undertook together with the Georgian ethnomusicologist Nana Mzhavanadze, to record village singers, to live and to study with them. The recording strategy employed during three field expeditions in 2015, 2016, and 2019, respectively, was especially designed for modern state-of-the-art computational analyses (Scherbaum et al., 2015, 2016, 2018a, 2018b, 2019; Scherbaum and Mzhavanadze 2018, 2020, 2021; Rosenzweig et al. 2022). Whenever possible[4], one singer from each voice group was simultaneously recorded with a high-quality headset microphone and a larynx microphone. In addition, the whole ensemble was recorded with a high-resolution (4K) video camera on which a directional microphone was mounted, plus a conventional stereo microphone. The systematic use of larynx microphones allowed the documentation of the acoustical contribution of each singer while all of them were singing together in their natural context without cross-talk artifacts (Scherbaum et al., 2015). This allowed us to study the mutual interactions between singers, which in this case were 'symmetric' (in the sense of Clayton, 2012), quantitatively for this dataset.

The third and most recent dataset, the Ozurgeti dataset, was specifically generated for the investigation of singer interaction at the level of physiological processes. It has been observed that the heartbeat rates of singers in a choir can synchronize, probably in

[3] We use the terms asymmetric and symmetric voice interaction in a manner similar to Clayton's (2012) use of these terms in the context of studying entrainment.
[4] During funerals, we refrained from using headset microphones for reasons of social propriety.

connection with their breathing. Müller and Lindenberger (2011) describe phase synchronization of respiration and heart rate variability (HRV) associated with choral singing in unison and in canon. In a study by Vickhoff et al. (2013) it was demonstrated that the HRV of choral singers is significantly affected by the structure of the music being sung. For example, unison singing of regular song structures makes the singers' hearts accelerate and decelerate simultaneously (Vickhoff et al., 2013). Motivated by these studies, during our field expedition in 2019 we conducted an experiment to monitor the singers' heartbeat rates during a two-hour-long recording session. For that purpose, we augmented our previously used recording equipment with (optical) pulse sensors taped to the index fingers of the singers. Heartbeat, audio, and video channels were time-synchronized via Bluetooth-generated time codes. As we will demonstrate, the resulting dataset now allows (to our knowledge for the first time) the investigation of the synchronization of heart rate variability of Georgian singers during the performance of complex songs.

The fact that traditional Georgian singers strongly interact with each other during their performances has been noted in scholarly literature at least as far back as Nadel (1933), but studying the related phenomena in a quantitative way has not really been possible until recently because of the lack of appropriate data. With the present paper, we want to demonstrate that the three datasets collected and analyzed within in the context of the GVM project remedy this situation.

As we will demonstrate, they now make it possible to analyze in detail (down to the level of individual notes) the harmonic intonation adjustments mentioned by Nadel (1933) to achieve harmonic consonance, and on the other hand to quantify the resulting systematic differences in melodic and harmonic tonal organization. Furthermore, we will demonstrate that harmonic coordination (which requires a high degree of singer interaction) is the dominating factor in the context of joint continuous pitch drifts that occur on the time scales of whole songs and which have been observed in particular for funeral dirges from Svaneti in northwest Georgia (Scherbaum and Mzhavanadze, 2020; Scherbaum et al., 2022).

For singers, harmonic intonation adjustments and intended joint pitch drifts can be both demanding and rewarding. On the demanding side, they require a high degree of mutual harmonic coordination. On the beneficial side, harmonic coordination, when successful, will be rewarded with the cognitive state of (sensory) consonance[5] (Cazden, 1962; Parncutt, 1989; Sethares, 2004). As a consequence, the investigation of singer interactions is seen as one way to advance the understanding of togetherness[6] in ensemble performances of traditional Georgian singing.

Observational Evidence for Harmonic Coordination in Traditional Georgian Singing

Asking Georgian singers and musicologists about their perception of the specifics of traditional polyphonic Georgian music, the first author has sometimes heard that it requires "vertical thinking" (cf. Scherbaum et al. 2020), in other words, the capability to 'think' in terms of harmonies instead of melodies. During our ethnomusicological field expedition in 2016, Ruben Charkhviani, a singer from Ushguli/Svaneti, was asked what non-Georgian singers do differently when trying to sing traditional Georgian music. His response – "They always want to come to the end" – was his way of expressing that traditional Georgian singing is not concerned about having to achieve something along a time axis (horizontally) but more with respect to the other voices (vertically). This phenomenon was reported in the scientific literature as early as the 1930s. Based on the analysis of phonograph recordings of Georgian singers recorded in prisoner-of-war camps in World War I (1914-1918), Siegfried Nadel (1933) wrote about the tonal organization of their polyphonic singing, as follows:

[5] It seems noteworthy in this context that the ambitus of (old) traditional Georgian songs is often rather small. Therefore, the fusion of overtones plays a considerable role in the perception of consonance and dissonance, such that the concept of sensory consonance becomes relevant.
[6] See also https://mdw.ac.at/togetherness/about/

> Finally, polyphony itself entails a change of tonal values of a different kind[7]. For it demands, especially at the main and resting points of the melodic line, pure consonances, or it generally favors the major third[8]; i.e., it demands simultaneous intervals which often do not coincide with the neutral or equal-distance ones of the melody. These simultaneous intervals must therefore be made possible by certain adjustments in intonation in the individual voices, which in turn can crisscross the intended melodic-tonal system…[9] (1933: 29)

Technically speaking, Nadel noticed that the intention of Georgian singers to maintain consistency of a melody with a fixed melodic scale was at times abandoned in favor of harmonic coordination, a process that requires a high degree of mutual interaction among the individual singers. Following Scherbaum et al. (2020), we refer to this process as 'dynamic intonation adjustment', which happens more or less instantaneously for the individual notes which are part of an harmonic interval or chord. In the following Section 2.1, we will discuss to what degree intonation adjustments can be identified in the Erkomaishvili and the GVM dataset, respectively.

Determination of Dynamic Intonation Adjustments from Recordings

One possible approach to measuring dynamic intonation adjustment is based on the analysis of pitch fluctuations of short pitch trajectories. Our hypothesis is that dynamic intonation adjustment introduces statistical dependencies between the pitch trajectories of two voices, which can be mathematically quantified through the analysis of the variances of the individual pitch trajectories and their differences. The theoretical basis is given by the fact that the difference of two uncorrelated Gaussian random variables (RV) is again a Gaussian RV with the mean being the difference of the means and the variance being the sum of the variances (Stirzaker, 1999). In the case of a correlation between the two RVs (as is expected in the case of pitch tracks where both singers try to maintain a particular interval despite fluctuations of the individual voices), the variance of the interval trajectory will be less than the sum of the individual variances. Figure 1

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[7] Previously, Nadel had discussed differences of the perceived melodic tuning system with respect to Western-European "church modes".

[8] The conjectured strong role of major thirds as a general feature in traditional Georgian singing could not be confirmed in recent investigations, except in city songs (e.g., Scherbaum et al. 2022).

[9] Die Mehrstimmigkeit selbst bringt schließlich eine Änderung der Tonwerte von anderer Art mit sich. Denn sie fordert, vor allem an den Haupt- und Ruhepunkten der melodischen Linie, reine Zusammenklänge, oder sie bevorzugt ganz allgemein die große Terz; d. h. sie verlangt Simultanintervalle, die oft mit den neutralen oder distanzgleichen der Melodie nicht übereinstimmen. Diese Simultanintervalle müssen daher durch gewisse Intonationsänderungen in den einzelnen Stimmen ermöglicht werden, die ihrerseits das intendierte melodisch-tonartliche System durchkreuzen können… (Nadel, 1933: 29).

shows two selected examples to illustrate this situation, one from the Erkomaishvili dataset (top panel), and one from the GVM dataset (bottom panel). In both cases, the variance reduction for the interval trajectory is more than 50%.

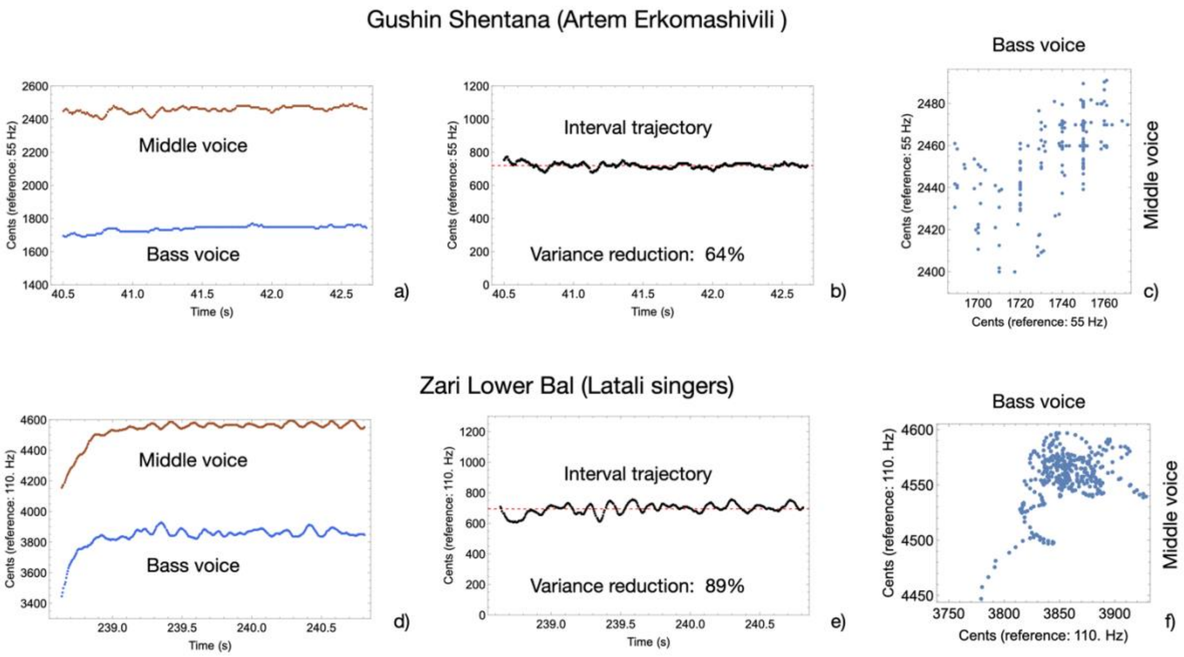

Figure 1. Examples for dynamic intonation adjustment. Fig. 1a, b, c, show the two pitch trajectories, their differences (interval trajectory), and the correlation plot, respectively, for a time window of approximately 2 sec from the chant *Gushin Shentana* (GCH-ID 10) from the Erkomaishvili dataset, maintaining a harmonic interval of a fifth. Fig. 1d, e, f, display an equivalent example for a funeral chant (*Zari*) from the GVM dataset (GVM-ID 203). The middle and bass voices in this case were sung by the two experienced singers Murad and Givi Pirthskhelani, respectively, from Latali.

Dynamic intonation adjustment requires considerable skills, both on the perceptual and the voice production side, since the mutual voice interaction happens essentially instantaneously and therefore subconsciously. Consequently, this phenomenon is not observed to the same extent in all ensembles in the analyzed data sets. Figure 2 shows the number of occurrences for all those dynamically adjusted harmonic intervals in the complete Erkomaishvili dataset (Fig. 2a) and a single funeral chant from the GVM dataset (Fig. 2b), which consist of notes longer than 0.5 seconds and for which the variance reduction of the interval variance was at least 50 percent.

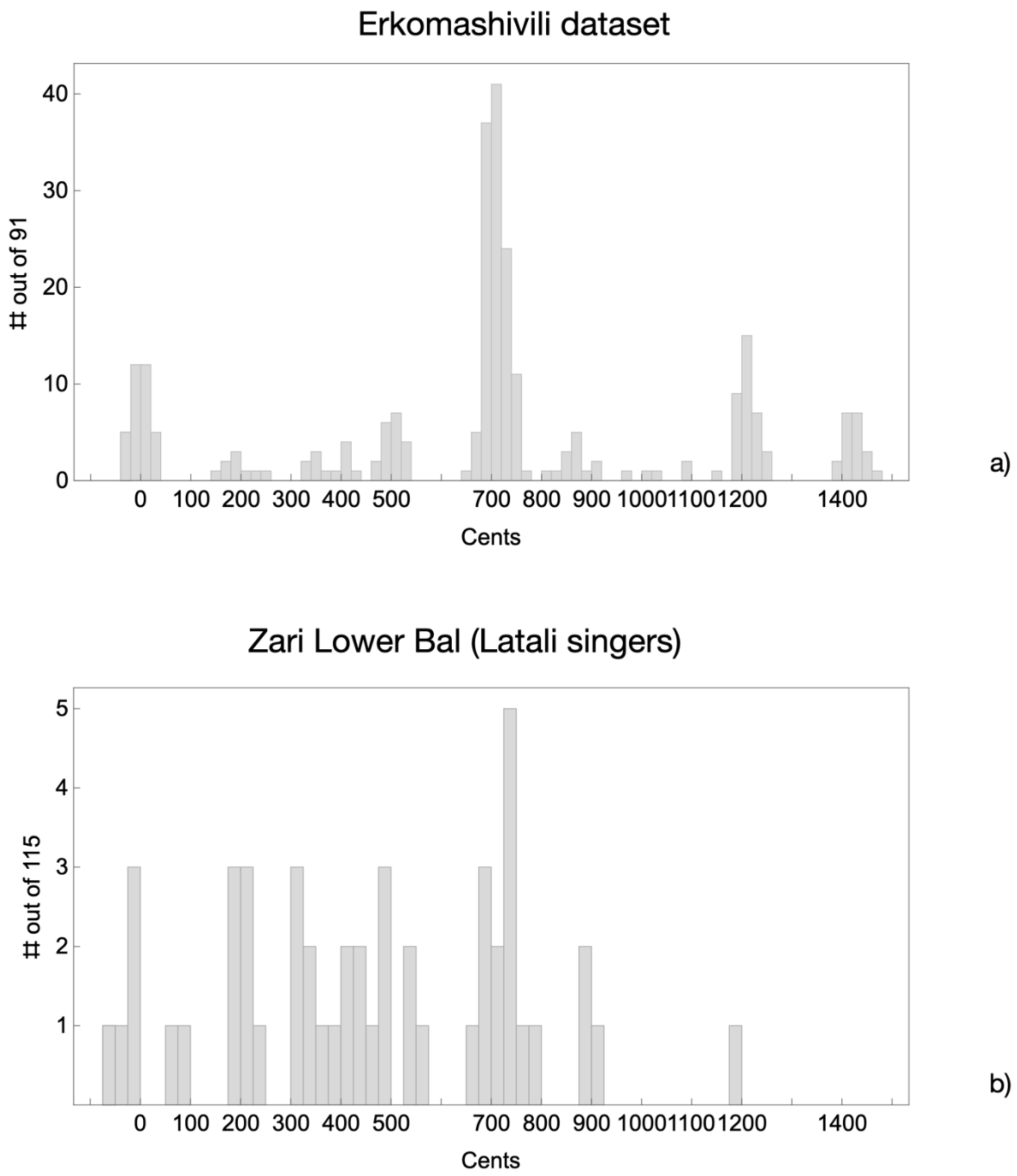

Figure 2. Histogram of the number of occurrences for all those dynamically adjusted harmonic intervals in the complete Erkomaishvili dataset (a) and a single funeral chant from the GVM dataset (b), which consists of notes longer than 0.5 seconds and for which the variance reduction of the interval variance was at least 50 percent.

As can be seen in Figure 2, dynamic intonation adjustment is particularly pronounced in the Erkomaishvili dataset (Fig. 2a), although examples of it are also visible in the example from the GVM dataset (Fig. 2b). In both sets of records, the fifth is the interval that is most often the subject of dynamic intonation adjustments. Furthermore, Artem Erkomaishvili, who was an exceptionally skilled singer, also seems to have been very careful to tune octaves, unisons, ninths, and fourths exactly to his liking.

Harmonically Controlled Pitch Drifts

The attempt to relate the fluctuations of the pitches of one voice to another on the time scale of the individual notes can be seen as a skillful illustration of the harmonic (vertical) musical thinking of experienced singers. To produce dynamic intonation adjustments is perceptually and technically demanding and examples of them are present, but not overly abundant, in the GVM dataset. Even more pronounced is another phenomenon that requires strong harmonic coordination, on a much longer time scale, namely over the course of an entire song. This is the phenomenon of joint continuous pitch drifts, which have been observed in particular for funeral songs from Svaneti (*Zär* aka *Zari*; Scherbaum and Mzhavanadze, 2020, Scherbaum et al., 2022). Fig. 3 shows a pronounced example of a *Zari* from Mestia, sung by singers from the nearby community of Zargash.

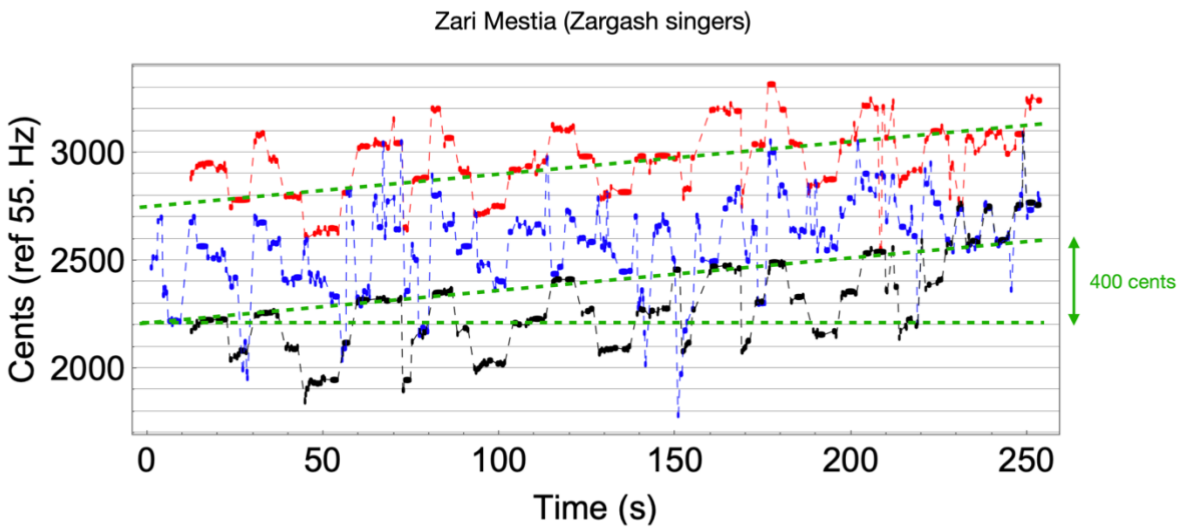

Figure 3. Trajectories of stable pitch segments of the *Zari* from Mestia, sung by singers from the nearby community of Zargash. The pitch difference between the begin and the end of the song is approximately 400 cents.

Note that the pitch drift is continuous and parallel for the individual voices, similar to a flock of birds that changes direction but maintains its geometrical integrity. By analogy, the singers maintain their relative melodic tuning systems (Scherbaum et al., 2022). This kind of harmonic coordination is often employed by singers from Svaneti. It is used inconsistently. i.e., by different ensembles not always for the same songs (cf. Scherbaum et al., 2022). In contrast to Western amateur choirs, where pitch drift is mostly downwards, the observed joint pitch drifts in Svan ensembles is nearly always upwards with average drift rates between 30-100 cents/minute. Since it is most prominent in funeral dirges, it seems to serve a group purpose, possibly to express collective pain and at the same time maintain a strong feeling of togetherness.

Consequences of Harmonic Intonation Adjustments

Since during (fast) harmonic intonation adjustments, 'melodic precision' is subordinated to 'harmonic precision' (e.g., by pitch bending to achieve harmonic intervals in a particularly pure way) this will have noticeable consequences for the tonal organization[10]. In the case of the Erkomaishvili and the GVM datasets, they lead to systematic differences between the melodic and harmonic scales (Table 1).

Table 1. Comparison of the scale models for the Erkomaishvili dataset (labelled AE) with the average tuning systems obtained for all Svan ensembles (labelled 2016 GVM) from Scherbaum et al. (2022).

Scale degrees	AE melodic	2016 GVM melodic	AE harmonic	2016 GVM harmonic
8	1231	NA	1217	1182
7	1052	NA	1043	1018
6	886	868	874	868
5	705	693	707	703
4	509	509	515	495
3	342	332	355	349
2	176	163	191	205
1	0	0	0	6

[10] Slow harmonically controlled pitch drifts affect the apparent tonal organization in such a way that prior to a tuning analysis they need to be adjusted (cf. Scherbaum et al., 2022; Rosenzweig et al., 2022).

The main difference between the melodic and harmonic scales is easy to understand if one considers that harmonic coordination aims at singing the harmonic fourth (close to 500 cents) and fifth (close to 700 cents) as purely as possible. To accommodate this, the approximately equidistant melodic scale (the step sizes in columns 2 and 3 in Table 1 are not very different from 171 cents) is then temporarily 'bent'. This then results in a smaller interval for the melodic second (close to 171 cents) than for the harmonic second, which often occurs as a byproduct of the 1-4-5 chord and is therefore about 200 cents. In this sense, differences in melodic and harmonic scales can be interpreted as possible side effects of harmonic coordination of polyphonic singing on the time scale of individual (important) notes.

Synchronization of Heart Rate Variability

Growing experimental evidence attests that music might actually modulate physiological functions and elicit biochemical effects (Cervellin & Lippi, 2011). The human heart plays a central role in this context. Together with the respiratory system, with which it is coupled by an effect called respiratory sinus arrythmia (RSA) (Ludwig, 1847), the heart functions as the engine of our lives by keeping our body's energy supply running. In addition, it acts as a sensory organ in a physiological sense (Shepherd, 1985), but also on a metaphorical level. For example, we speak of 'something going to our heart' when it touches us emotionally.

Chew and coworkers (2020) have shown that "Every heart dances to a different tune", in other words that the reaction of the heart to music is very subjective. One the other hand, it has also been found that the heart rates of singers in a choir can synchronize, probably in connection with their breathing. As noted earlier, Müller and Lindenberger (2011) describe phase synchronization of respiration and heart rate variability (HRV) associated with choral singing in unison and in canon. In a study by Vickhoff et al. (2013) it was demonstrated that the HRV of choral singers was significantly affected by the structure of the music being sung. Unison singing for example of regular song structures makes the hearts of the singers accelerate and decelerate simultaneously (Vickhoff et al., 2013).

We wanted to test if these effects could also be observed for more complex song structures. In July 2019, together with Lasha Chkhart'ishvili (bass voice), Guram Guntadze (middle voice), and Mamuka Siradze (top voice) from the trio Khelkhvavi in

Ozurgeti, we conducted an experiment to monitor the singers' different heart rates during singing. During a recording session, which lasted about two hours, we augmented our recording equipment with (optical) pulse sensors taped to the index fingers of the singers (Fig. 4). Heartbeat, audio and video channels were time-synchronized via Bluetooth-generated time codes (Tentacle Sync).

Figure 4. Trio Khelkhvavi from Ozurgeti. From left to right: Lasha Chkhart'ishvili (bass voice), Guram Guntadze (middle voice), and Mamuka Siradze (top voice).

For the analysis of the recordings, we wanted to make sure that the singers were already well tuned to each other but also that the song was sufficiently complex. These two requirements let us choose the Gurian folk song Chven Mshvidoba, which was sung close to the end of the session.

The individual pulse sensor recordings are subject to high frequency noise (Fig. 5a). After lowpass filtering, (Fig. 5b) the signal-to-noise ratio visibly increases, in particular for the recording of the top voice singer. Nevertheless, the heartbeat recording quality still differed strongly for the individual singers, possibly due to differences in the individual sensor couplings.

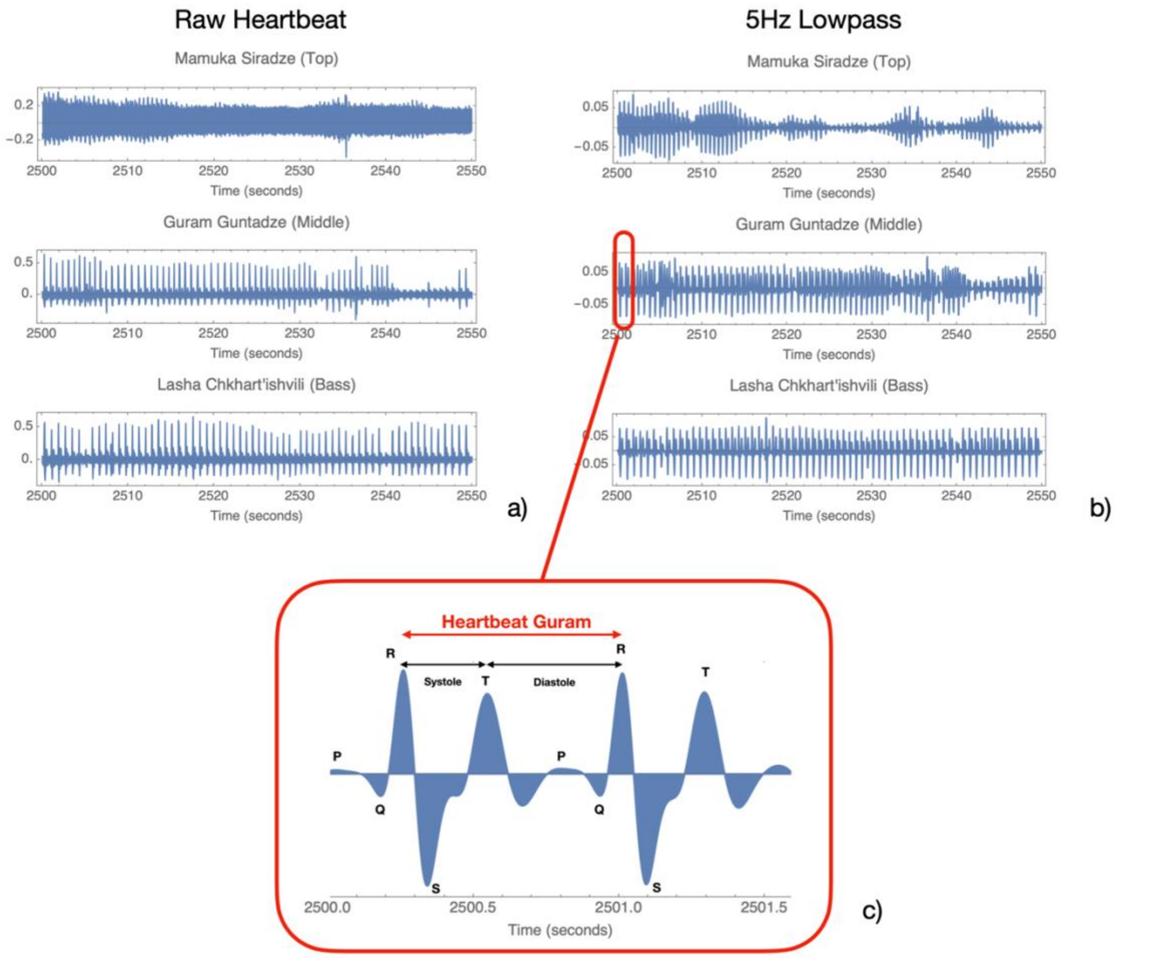

Figure 5. Panel a) Raw heartbeat recording of the three singers for a selected time window of 50 seconds duration. Panel b) Heartbeat recordings lowpass filtered at 5 Hz. c) Two seconds of Guram's heartbeat, lowpass filtered at 5 Hz.

For all of the singers, one can clearly recognize all the typical deflections seen on an electrocardiogram (ECG or EKG). The so-called QRS complex[11], in Fig. 5c) amplified for the middle voice singer Guram, is the most visually obvious part of the trajectory and corresponds to the activation of the ventricles of the human heart and the contraction of the large ventricular muscles. The systole is the tightening and thus blood outflow phase of the heart in contrast to the diastole, which defines the relaxation and thus blood inflow phase of the cardiac cycle.

Since the quality of individual pulse sensor recordings differs as a function of time but also depending on the achieved sensor coupling, the robust and reliable extraction of a

[11] https://bvns.net/wp-content/uploads/2018/10/Cardiology-the-ABC's-of-the-PQRST.pdf

continuous sequence of heartbeats constitutes a challenging task.

In the present case, the problem was approached using the concept of Predominant Local Pulse (PLP) functions (Grosche and Müller, 2011; Müller, 2015; 2021) for which the main constituents are shown in Fig. 6. The novelty function (Müller, 2015; 2021) shown in Fig. 6a encodes the most prominent heartbeat signals' amplitude changes over time. It provides the basis for the calculation of a time-tempo representation (Fig. 6b), the so-called tempogram (Müller, 2015; 2021).

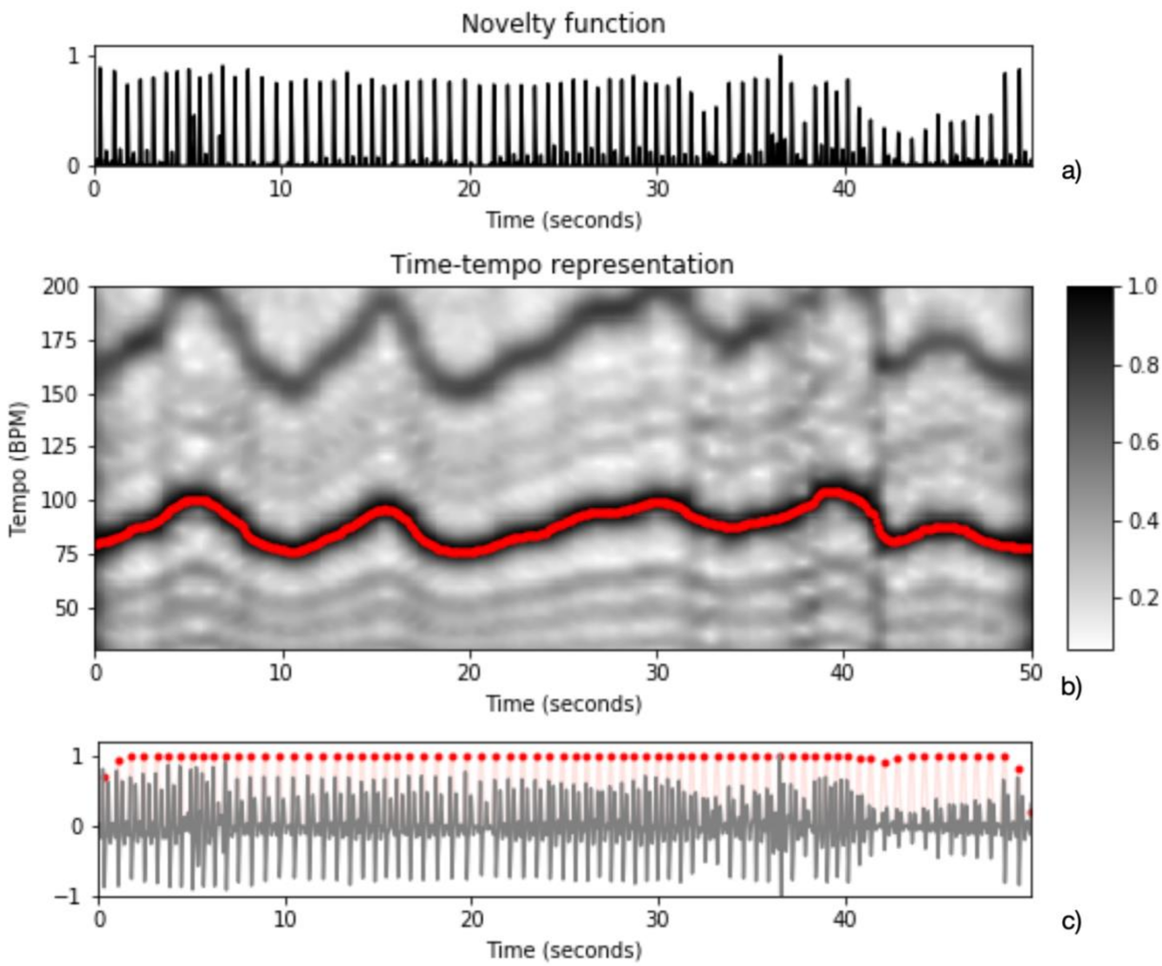

Figure 6. a) Novelty function for the heartbeat of the middle voice singer. b) Corresponding tempogram (time -tempo representation). c) Predominant Local Pulse (PLP) function (in red) and selected peaks (red dots), superimposed on the lowpass filtered heartbeat recordings.

The key idea behind the tempogram concept is to locally compare the novelty function with windowed sinusoids. Based on this idea, for each time position, a windowed sinusoid is calculated that best captures the local peak structure of the novelty function. Instead of looking at the windowed sinusoids individually, the crucial idea is to employ an overlap-add technique by accumulating all sinusoids over time. As result, one obtains a single function that can be regarded as a local periodicity enhancement of the original novelty function. Revealing predominant local pulse (PLP) information, this representation is referred to as a PLP function (Fig. 6c). The PLP function can be regarded as a pulse tracker (in our case the heartbeat) that can adjust to continuous and sudden changes in tempo as long as the underlying novelty function possesses locally periodic patterns (Müller, 2015; 2021).

In order to quantify the heart rate variability (HRV) of the singers, we followed the work of Vickhoff et al. (2013) and Wang and Huang (2012) and chose RMSSD, which is defined as the root mean square of successive normal RR intervals (Wang and Huang, 2012). Specifically, we calculate RMSSD as the root mean square of the distances of successive PLP peaks (Fig. 7). To get a rough view of the entire recording session, a window length of 30 seconds was chosen for the RMS calculation. This results in sufficiently smooth curves which enable the comparison of the individual singers but still preserve some details.

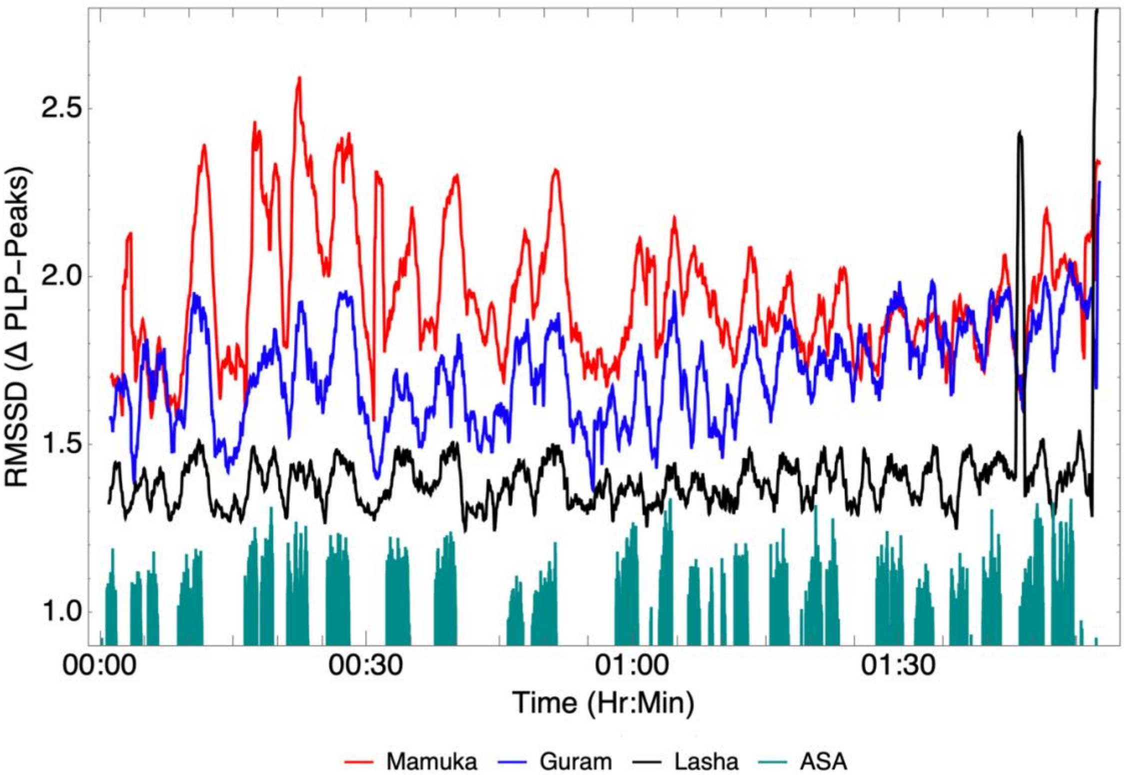

Figure 7. The red, blue, and black lines show the RMSSD values, which describe the change in heart rate in a root-mean-square sense, for the three singers. The green curve shows the average singer activity (ASA), averaged over 30 seconds.

As can be seen in Fig. 7, there is a strong correlation between the RMSSD trajectories of the individual singers during the whole recording session. This means that the hearts of the singers accelerate and decelerate simultaneously on the time scale given by the averaging window of 30 seconds. A likely explanation is the coupling of HRV to respiration (cf. Vickhoff et al., 2013). This is because with this long time scale there should be a correlation between singing or not singing and respiration, and via respiration also with heart rate activity. In other words, there should be a correlation between the RMSSD trajectories and phases where the singers were singing and when they were not. This can indeed be seen from the comparison of the RMSSD trajectories with the average singers activity (ASA), which is calculated by thresholding the sum of the individual RMS amplitudes of the larynx microphones.

For a more detailed analysis, we selected the Gurian folk song Chven Mshvidoba, which was sung close to the end of the recording session. For its analysis we chose a shorter time window (10 sec) for the RMS calculation in order to be able to perceive more detailed variations in heart rate variability (Fig. 8). In particular, the two upper voices (Guram and Mamuka) show a clear correlation between their RMSSD trajectories for the duration of the whole song (Fig. 8a). This means that the hearts of Guram and Mamuka accelerated and decelerated more or less simultaneously on the given time scale. In contrast, the RMSSD trajectory of the bass voice singer (Lasha) showed less amplitude variations and no clear correlation to either the middle or the top voice.

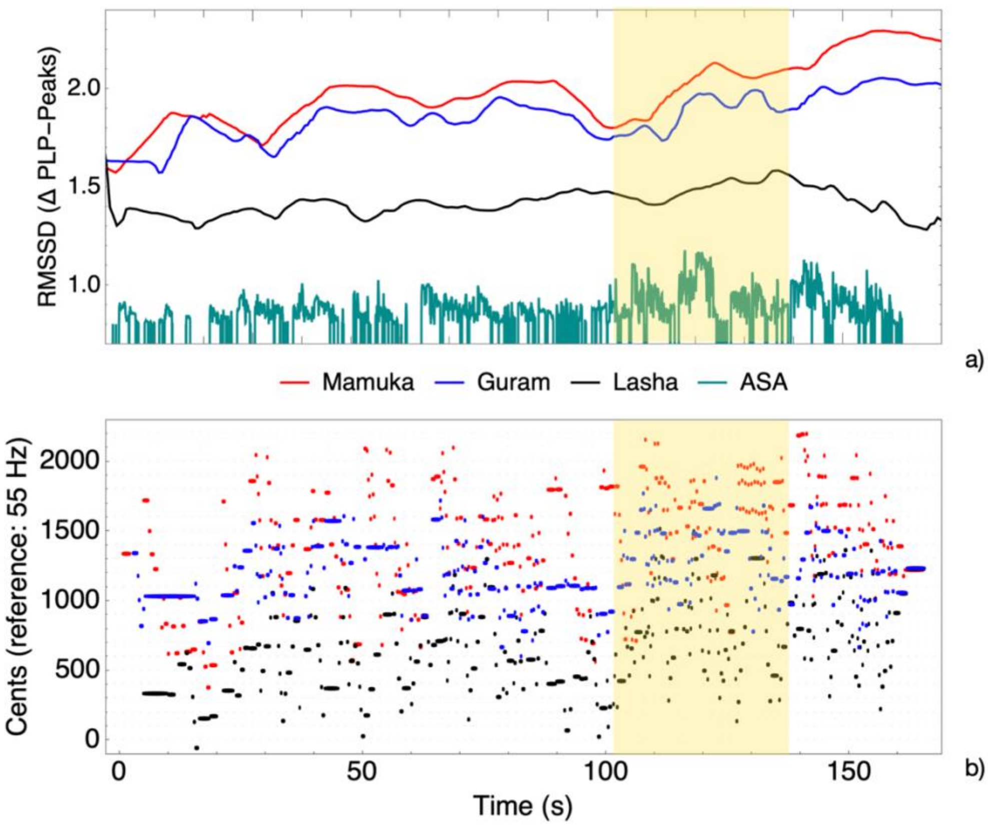

Figure 8. a) RMSSD values describing the change in heart rate in a root-mean-square sense, for the three singers. The green curve shows the average singer activity (ASA) for the top and the middle voice. b) Note trajectories for the individual voices, calculated with the help of the Tony software (Mauch et al., 2015).

These observations are consistent with the dynamics of the song, since the interaction between the two upper voices is the most dynamic, especially during the time window marked in yellow, while the bass voice has a less dynamic, more supporting role. During the highlighted time window, the ASA curve for the two top voice singers shows rising and falling phases which are presumably also reflected (with a slight time delay) in the breathing activity and then, via the RSA mechanism (Vickhoff et al., 2013), in the synchronized heart rate accelerations and decelerations of Guram and Mamuka. In the video of the recording[12], one can observe how the dynamics of particularly the two top voice singers jointly increased towards the end of the song. This goes hand in hand with an overall pitch rise of all three voices towards the end of the song which can be seen in

[12] See the link, https://www.uni-potsdam.de/fileadmin/projects/soundscapelab/Videos/ChvenMshvidobaOzurgeti.mp4

Fig. 8b. These results are quite encouraging and suggest that there is a lot of new and relevant information to be gained from the joint use of different sensor types during ethnomusicological recording sessions.

Conclusions

Although the primary purpose of the present paper was to report measurable signs of singer interaction and togetherness in performances of traditional Georgian singing, we feel that its implications go beyond that technically oriented goal. In addition to harmonically controlled intonation adjustments on short (dynamic intonation adjustments) and long timescales (continuous pitch drifts), we feel that differences in melodic and harmonic scales can also be interpreted as (side) effects of singer interaction with the possible goal to achieve harmonic togetherness (or consonance) on the time scale of individual (important) notes.

The present results also demonstrate some of the potential benefits for the analysis of non-western oral music traditions when integrating new sensor types into ethnomusicological field recording sessions, resulting in new types of multimedia, and multi-channel recordings including video, audio, muscle vibrations, heartbeat, and respiration signals. Our experiment shows that such measurements can provide relevant information about the synchronization of body functions of singers during performances. We have shown that these types of experimental setups are no longer limited to a laboratory setting, but can be conducted in a 'real-world' environment (even in very remote regions) with reasonable technical and logistical effort, thus also allowing to address questions about the 'ecological validity' (Holleman et al., 2020) of these types of measurements.

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