Nonlinear Phenomena in Contemporary Vocal Music

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Complex and multiphonic voice signals of vocal improvisors are analyzed within the framework of nonlinear dynamics. Evidence is given that nonlinear phenomena are extensively used by performers associated with contemporary music. Narrow-band spectrograms of complex vocalizations are used to visualize the appearance of nonlinear phenomena (spectral bifurcation diagrams). Possible production mechanisms are discussed in connection with previous research, personal performance and pedagogical experience. Examples for period doubling, biphonation and irregular aperiodic phonation in vocal sonorities of contemporary vocal improvisors are given, and glottal whistle production encompassed with biphonation and triphonation is shown. Furthermore, coincidences of harmonics-formant matching associated with abrupt transitions to subharmonics and biphonation in the vocal output are provided. This also shows the recurrent use of nonlinear phenomena by performers. It is argued that mechanisms such as source-tract coupling or vocal fold desynchronization due to asymmetry are used in a reproducible way for musical tasks.

Key Words: Contemporary vocal music—nonlinear dynamics—multiphonic complex sonorities—artistic reproducibility—glottal whistle.

I. INTRODUCTION

Composers, performers and listeners of contemporary classical music have long recognized the vitality of complex multiphonic instrumental and vocal sonorities. However, the theoretical understanding of these complex sounds relied mainly upon the methods of mechanical reproduction (i.e. fingering charts with embouchure indications), while scientific questions were largely avoided (except e.g. 1).

Beginning in the early 1980's, theories of nonlinearity were applied to complex musical signals. This led some to reconceptualize their understanding of the elements involved in the production of sound. During the last decade, when combined with the knowledge gained through analog/digital sound synthesis, a conception of a scalable parameter space applied to instruments and voices was developed. This scaling suggests that selected parameters may be systematically varied between minimal and maximal values to produce new complex sonorities.

In this paper, complex and multiphonic voice signals from vocal improvisors will be analyzed within the framework of nonlinear dynamics. We classify voice samples from solo vocal improvisations as being harmonic voice, subharmonics, biphonation (two independent pitched melodies) or irregular aperiodic behavior.

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Nonlinear phenomena in voice are widely observed in newborn cries,[2,3] pathological voices,[4–8] animal vocalizations,[9–12] and occasionally in speech.[13,14] Further, it has been reported that nonlinear vocal phenomena carry functional and communicative relevance for animals and humans.[15,16]

In a previous case study, Paul Ward[17] investigated vocalizations of a teenage subject who had the ability to produce biphonation. This subject achieved such behaviors through asymmetrical control of the left and right vocal folds. Captured on high speed photography and cinefluorography, the subject demonstrated the capacity to produce two different, but simultaneous pitch movements, otherwise having a completely normal voice. Further, she had the proficiency to produce such behaviors within clearly identifiable musical scales and not simply as contour relationships.

This study is representative of a growing body of evidence that suggests normal larynges have the ability to produce nonlinear phenomena including subharmonics,[18–21] biphonation[17,22–24] and aperiodic, irregular behavior (deterministic chaos).[21,25–27] In addition, it has been documented in the musical literature that these and many other non-standard vocal outputs are widely used by performers of contemporary music.[26,28–39] Here we provide a framework to characterize these frequently used nonstandard vocalizations in contemporary vocal music and discuss possible physiological mechanisms.

In this paper, we document the extensive use of temporally and spectrally complex vocalizations by performers of contemporary vocal music within the framework of nonlinear dynamics. We discuss the observed complex temporal and spectral patterns using the terminology of nonlinear phenomena. Musically, we argue that nonlinear phenomena in the voice can be consciously used for artistic purposes.

A. Nonlinear phenomena

The human voice production system can be considered as multiple nonlinear coupled oscillators (e.g. left and right vocal folds, different modes of vibrations within single folds, ventricular folds, epiglottis, aerodynamical oscillators).[40] The vocal folds disrupt the outward flowing airstream using a wavelike vibratory motion. This oscillation is driven by the airflow provided by alveolar (lung) pressure together with visco-elastic forces within the larynx to produce phonation. The theoretical description of normal periodic phonation requires already a nonlinear theory, describing e.g. phonation onset from prephonatory standstill as an instability of the rest state resulting in self-sustained oscillations. Furthermore, nonlinear laws govern the dependence of normal phonation upon the driving pressure, rate of airflow, amplitude of vocal fold oscillation, stress-strain properties of vocal fold tissue and vocal fold collision.

In this paper we focus on vocal behaviors of vocal improvisors that deviate from normal periodic phonation. In the following discussion the term nonlinear phenomena will consequently refer to subharmonics, biphonation, and irregular aperiodic phonation (associated with deterministic chaotic behavior).

1. Principles

Understanding the dynamics of nonlinearly coupled oscillators requires an introduction to a few basic concepts of nonlinear dynamics. A detailed introduction to nonlinear dynamics is beyond the scope of this paper and can be found elsewhere.[7,41–43] Here we sketch only briefly the basic ideas.

Oscillating systems are omnipresent in the physical, biological and chemical worlds. These systems share the common feature to be able to self-sustain a periodic behaviour. Coupling several oscillators, even just two, can generate highly complex temporal patterns of motion for the overall system, even more complex than the individual oscillators. The analysis of real-world phenomena produced by several coupled self-sustained oscillators uses methods from nonlinear dynamics theory. Therefore, the behavior of a real-world system is mapped into phase space. The phase space is built from the dynamical variables (e.g., for a mechanical mass-spring oscillator these variables would be the excursion from the resting position and the velocity of the mass attached to the spring) necessary to determine the state of the system. At every time point, the behavior of a system may be represented by a single phase space point.

There are qualitatively different sorts of complex vibratory patterns of nonlinearly coupled oscillators.

In the corresponding phase space representations these patterns are characterized by different geometrical objects, termed attractors. In the simplest case the oscillators cease to move at all; the system reaches a static equilibrium. This attractor is termed 'steady state' and can be represented by a single point in phase space. When the coupling between the oscillators synchronizes their vibrations, the overall behavior is a periodic, regular oscillation. Technically, such a periodic self-sustained oscillation is termed 'limit cycle'. In phase space a limit cycle attractor forms a closed loop. The natural frequencies of two oscillators can be quite different from each other. Then, coupling can still synchronize or entrain these oscillations, but the resulting frequency might be quite different from the natural ones. For instance, two oscillators with a frequency ratio of approx. 1 : 2 will be entrained to a ratio of exactly 1 : 2. Then the overall system output will have the frequency of the slower oscillator. This behavior is termed 'subharmonic oscillation' or 'folded limit cycle', which can be represented as a folded closed loop in phase space. If the coupling between oscillators is weak, oscillators can vibrate freely with independent frequencies not related as integer multiples. Then, the phase space representation is a 'torus', a two-dimensional object in phase space, as the overall system (i.e. the superposition of at least two oscillators) never exactly repeats itself. Eventually, two desynchronized coupled oscillators can generate nonperiodic, irregular vibrations. This behavior that never repeats but that is still bounded is termed '[deterministic] chaos'. For the sake of clarity the term 'deterministic' is used to stress the absence of any random influences on the system. In phase space, deterministic chaos forms a limited complex geometrical object that has a fractal, noninteger dimension.

Different sorts of vibratory patterns govern the dynamics of nonlinear coupled oscillators for constant control parameters of the system – for example vocal fold tension or subglottal pressure. Above, we described the most prominent attractor types steady state, [folded] limit cycle, torus, and [deterministic] chaos. Often, external control parameters vary slowly compared to the typical dynamical behavior, e.g. vocal fold vibrations. A slowly varying parameter can induce sudden, abrupt transitions between different attractor types – a behavior termed bifurcation. In this paper a few bifurcation types are of particular relevance: The transition from the rest state (steady state) to a limit cycle is termed 'Hopf bifurcation.' An abrupt change from a limit cycle to a folded limit cycle (subharmonic oscillation) is termed 'period doubling bifurcation'. When another independent oscillation appears in a vibrating system, this transition from a limit cycle to a torus is termed 'secondary Hopf bifurcation.' Often, either cascades of period doubling bifurcation or secondary Hopf bifurcations are precursors of the sudden onset of deterministic chaos. In other words, a small control parameter shift then induces an abrupt change of the system output to nonperiodic, irregular behavior.

2. Applications to voice production

The framework of nonlinear dynamics can be used to classify complex vocal behavior of (contemporary) vocal improvisors. Steady state behavior occurs when the vocal folds are at rest. Then as subglottal air pressure increases, a Hopf bifurcation changes the steady state attractor into a limit cycle as the vocal folds begin to vibrate in a normal, periodic way. Often during speech and song, period doubling bifurcations occur which can then be seen as subharmonic oscillation. Subharmonics may be classified as a special type of limit cycle which appears via transition from a periodic oscillation to an oscillation with alternating amplitudes. Less frequent, though still seen in speech and song, are phenomena featuring two or more independent frequencies. This phonation, geometrically classified as a torus in phase space, may be produced with asymmetrical vocal fold vibration and has been termed biphonation.[7,44] As mentioned above, subharmonics and tori often are precursors of deterministic chaos. In this case, the behavior is nonperiodic, irregular and complex, but not necessarily random.

In order to provide evidence of deterministic chaos, phase space analysis is required.[2,7] In earlier studies attractor dimensions and Lyapunov exponents have been estimated from voice signals.[45–50] A comprehensive phase space analysis of different attractors of voice signals is beyond the scope of this paper (for attractor dimensions, Lyapunov exponents see e.g. 27,51–53. For rigorous mathematical and statistical tests of the presented data

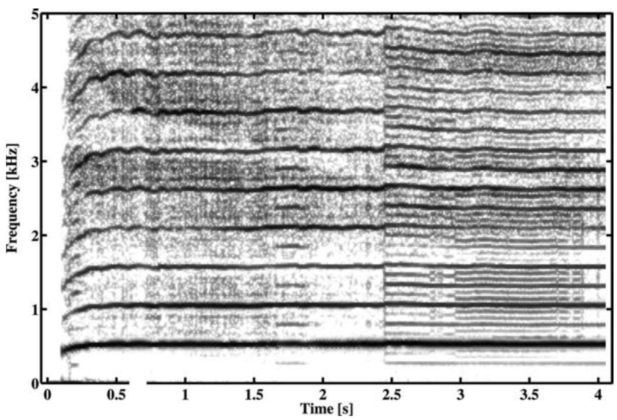

FIGURE 1. Period doubling cascade from a harmonic behavior with a pitch of about 500 Hz to subharmonics at 1/2, 1/4 or 1/6 of the pitch (Sample from solo vocal improvisation *investigazioni (diplofonie e triplofonie)* by the vocal improvisor Demetrio Stratos.[65]

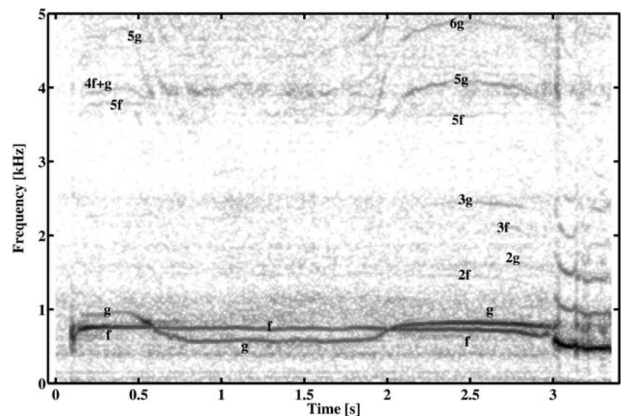

FIGURE 2. Biphonation with two independent frequencies (two independent pitched melodies) termed *f* and *g* and various linear combinations of these frequencies (Sample from solo vocal improvisation *passagi 1,2* by the vocal improvisor Demetrio Stratos.[65]

the data are available on request). Fortunately, many conclusions about the dynamics can be drawn from narrow-band spectrograms. These can be interpreted as spectral bifurcation diagrams where time is considered a control parameter (cf. 54–56): Subharmonics (e.g., see Fig. 1) after period-doubling bifurcations correspond to parallel lines in between harmonics. These occur typically at multiples of 1/2, 1/3 or 1/4 of the original pitch, generally at n/m of the original pitch, where n and m are small integers. In the case of biphonation (e.g. Fig. 2), seemingly independent spectral components with no simple ratio (such as 1/2, 1/3), that are modulated differently or move independently, appear in the spectrum. Finally, chaos (see Fig. 3) is characterized by broadband noise-like segments that appear via abrupt transitions. Distinct spectral peaks embedded in the broadband spectrum appear due to recurrent quasiperiodic behavior within the chaotic segment. Deterministic chaos is often interrupted by windows of normal periodic phonation or subharmonic phonation.

II. MUSICAL PHENOMENA

Nonlinear phenomena have been well-documented in many disciplines, but regularly ignored by the mainstream of performers and composers of contemporary classical vocal music who treat the voice with much the same musical aesthetic and principles of phonation that existed during the 18th and 19th centuries. So that while instruments have incorporated multiphonics, complex inharmonic signals and other transient phenomena,[1,57] the voice has remained for the most part the carrier of simple melodic formuli.

Nonlinear phenomena have been identified as important instrumental resources for experimental new music since the late 1950s when Bruno Bartolozzi attempted to systematize a framework for the production of multiphonic sonorities for woodwinds.[58] These innovations, combined with the continuing technical development and conceptual radicalism of electroacoustic music, suggested to many that the voice should share in the wealth of new sound and its construction. Therefore during the 1960s, composers such as Dieter Schnebel, Luciano Berio, John Eaton, Giacinto Scelsi, György Ligeti, Kenneth Gaburo, Pauline Oliveros, Sylvano Bussotti, Robert Erickson and Mauricio Kagel began to explore the production and organization of non-standard vocal music.[59] However, most of this work did not attempt to systematically utilize nonlinear phenomena. This is completely understandable, for unlike instruments, the human voice cannot easily be taken apart and put back together. Combined with the lack of standardized fingering charts for vocal sound production within the larynx, most composers attempted

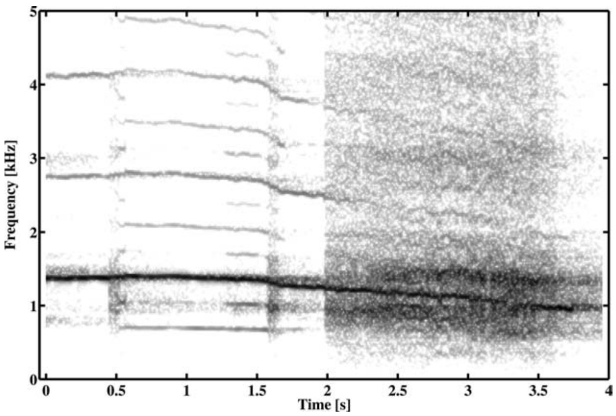

FIGURE 3. Transition from harmonic behavior via period doubling, period quadrupling to an irregular, noise-like segment, where the vocal tract filter is revealed by different shadings (Sample from solo vocal improvisation *entre nosotros - epitafio a las ballenas* by the vocal improvisor Fatima Miranda.[63]

to explore performance technique and expression through phonetic based articulatory procedures or to a far lesser degree through the combination of multiple vocal sound sources, combining primarily harmonic with inharmonic input, or special phenomenon, such as subharmonics or overtone singing. In the last two decades of the 20th century, the active search for expression through the vocal instrument has subsided and new compositions again feature mostly traditional modes of vocal performance. However, nonlinear phenomena of the voice are extensivelly used by performers who are often classified as vocal improvisers.

For this study, complex vocalizations from solo vocal improvisations by vocal improvisors Greetje Bijma,[60] Jaap Blonk,[61] Anna Homler,[62] Fatima Miranda,[63] David Moss,[64] and Demetrio Stratos[65] were chosen. We show examples for the appearance of nonlinear phenomena in these singers and provide ideas about possible production mechanisms. We argue that these mechanisms are used in a reproducible way for musical tasks.

III. MATERIAL AND METHODS

We present narrow-band spectrograms as time-frequency plots of sound samples of vocal improvisors. Narrow-band spectrograms can be interpreted as spectral bifurcation diagrams where time is considered a control parameter.[54–56] The samples were recorded at a sampling rate of 44100 Hz with a resolution of 16 bits/sample. For the calculation of the spectrograms we used a window size of 2048 sample points for the Fourier analysis. Therefore the frequency resolution can be calculated as 44100/2048 Hz≈21.5 Hz which corresponds to the smallest frequency of the Fourier analysis. We used a Hanning window for the Fourier analysis to account for finite window size effects. The sound signals were centered about their mean values. A temporal overlap of 2000 sample points was used for the sliding window Fourier analysis. If not otherwise specified, the dynamical range of the spectrograms was chosen as 60 dB sound intensity level. All spectrograms were normalized with respect to their maximum intensity level. A high spectral resolution of 21.5 Hz rather than a high temporal resolution was chosen for the calculation of the spectrograms. We assume that in vivo physiological parameters, such as vocal tract configuration or subglottal pressure change slowly over time[66] which can still be resolved by the low temporal resolution of the spectrograms.

All samples were recordings from single singers only. The singers are vocal improvisors performing solo vocal improvisations with no processing. In musical terms, their articulary gestures can be described as nonturbulent open vowel-like sonorities. These improvisors aim to reach an artistically pleasing and highly cultured state. All recordings consist of the pure microphone signal without post-processing, neither dynamically (dynamical compression or enhancement) nor spectrally (filtering, pitch shifting, chorusing, phasing). The sound samples were digitally copied from publicly available CD recordings.

Our study is based on voice samples that were chosen from 300 different samples of 7 different singers. We chose the shown representative subset of samples due to preliminary perceptual evaluation concentrating on episodes with independent frequencies, fast transitions, pitch instabilities, whistle like vocalizations and broadband sounds. With respect to contemporary music, voice samples were selected that combine artistically interesting multitone complex vocal sonorities with dynamically interesting nonlinear phenomena.

IV. RESULTS

In Fig. 1 we show an example of period doubling with windows of inharmonicity. At 1.6 s a period doubling bifurcation (P2) occurs indicated by an additional stack of harmonics interspersed between the existing harmonics. At about 2.5 s a period quadrupling bifurcation (P4) occurs, at 2.7 s a bifurcation to a period sextupling (P6) appears – a period six times the fundamental pitch. After a P4 bifurcation (2.8 s) the system jumps via a P6 bifurcation again (3.0 s). The fundamental frequency of about 500 Hz suggests that the vocal folds of the male singer vibrate in the falsetto register of a male voice. This finding is consistent with our perceptual judgement.

In Fig. 2 we show an example of biphonation, the occurrence of two independent frequency contours that may be perceived as two different pitch sequences (melodies). At about 0.6 s and about 2.0 s the time course of the two frequencies crosses, which supports our observation of independence of the two frequencies. In addition to the two independent frequency contours f and g, we observe frequency components which can be explained by linear combinations of f and g. During the biphonic episode the amplitudes of the combination frequencies are relatively small, indicating that the amount of coupling between the oscillators is low. At about 3.0 s a register transition to a nonbiphonic falsetto voice occurs, revealing stronger harmonic components than during the biphonic episode.

In Fig. 3 we give an example of a female voice with a sudden transition from normal, harmonic phonation to one with a broadband spectrum. In this example, sequences of period doubling and quadrupling bifurcations appear before the onset of irregular aperiodic oscillation. Within the irregular segment, starting at about 2.0 s, we can see residual spectral components related to the previous harmonic components. Additionally, formants at approximately 1.0 kHz, 1.4 kHz and 3.0 kHz can be seen. The subharmonic components bifurcating at about 0.5 s and approximately 1.3 s are perceived as time varying mixtures of harmonic and inharmonic components.

In Figures 4 and 5 we present examples in which time-varying formant frequencies matching harmonics coincide with bifurcations to subharmonic regimes. Fig. 4 is the visualization of an extremly high and light fundamental frequency of a female voice at about 1.25 kHz modulated by a tremolo frequency of about 4 Hz. Sidebands of the second harmonic appear when the upward moving formant frequency matches the second harmonic at about 1.0 s (arrows). The result is to reinforce the amplitude of this harmonic. The sidebands of the fundamental frequency and the third harmonic are also visible, but lower in intensity than the sidebands of the second harmonic.

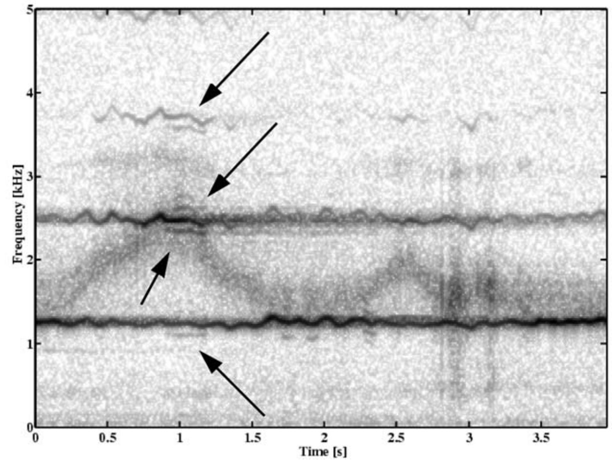

FIGURE 4. Coincidence of formant matching harmonic associated with sideband modulations of harmonic component (arrows) (dynamical range: 90 dB sound intensity level) (Sample from solo vocal improvisation *in principio* by the vocal improvisor Fatima Miranda.[63]

In Fig. 5 we show an example of a formant matching harmonics associated with a period multiplying bifurcation. A male singer used the falsetto register to phonate at about 550 Hz. In Fig. 5, a formant frequency coincides with the the fourth harmonic around 0 s (arrow). At the same time period quintupling (P5) occurs. Then, from 0.5 s to 1.5 s the formant frequency moves downward and coincides roughly with the third harmonic at about 1.5 s (arrow). At this point period quintupling (P5) occurs.

In Fig. 6 we show recurrent instances of abrupt transitions from regular phonation to sub-harmonic and irregular phonation. The female voice produces phonation at nearly 900 Hz. The left part of Fig. 6 begins with an irregular segment with a periodic window followed by another irregular segment. At about 1.0 s an extremely high and light phonation with an increased perception of pitch sets in. Note

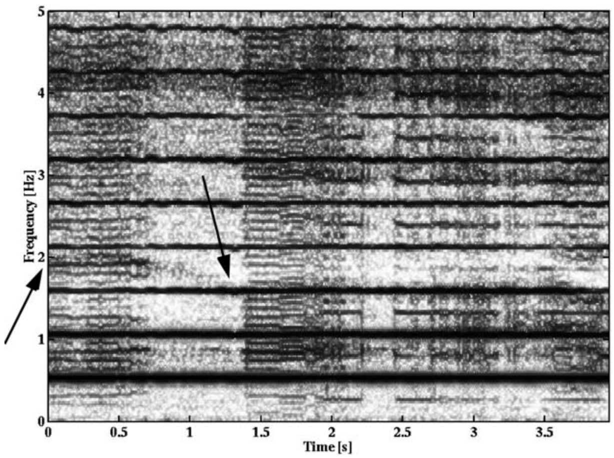

FIGURE 5. Recurrent source-formant interaction: Formant induced P5 bifurcation with five subharmonics vanishing and reappearing when a formant frequency matches the fourth or the third harmonic, respectively (arrows). (dynamical range: 90 dB sound intensity level, figure contrast and intensity manually adjusted to emphasize formants) (Sample from solo vocal improvisation *investigazioni (diplofonie e triplofonie)* by the vocal improvisor Demetrio Stratos.[65]

that about 1.0–2.5 s the frequency component of 900 Hz is an artefact of the recording environment and is the result of excess reverberation during recording, and is not representative of phonation. At about 2.5 s a transition to a chaotic segment with residual harmonics occurs followed by harmonic windows with subharmonics including P6 at 3.3 s. At about 3.4 s a chaotic segment with residual harmonics starts, which is interrupted by short instances of subharmonic windows. In the right part of Fig. 6 the qualitative behavior is similar, although details vary. At about 0.4 s the high and light phonation bifurcates to a chaotic behavior. This segment is interrupted by a subharmonic window. After the chaotic segment the voice transitions again to high, light phonation. At about 2.5 s another chaotic segment starts which, again, is interrupted by a subharmonic window at about 3.2 s.

In Fig. 7 we observe a female 'glottal whistle' starting at a pitch of above 2.0 kHz descending to about 1.5 kHz. After the initial 'glottal whistle', a second frequency of approx. 3.5 kHz appears at about 1.0 s and is functionally independent. At 2.0 s a third frequency shows up which vanishes at about 2.5 s. As the two remaining frequency contours descend further, we observe multiple combination frequencies increasing in amplitude. This increase of intensity can be related to an increase of coupling over time between the two independent frequencies. At about 5.4 s a third component appears which perceptually has a vocal fry-like character.

V. DISCUSSION

In this paper we have shown examples of the intentional use of nonlinear phenomena in contemporary vocal music. In multi-tone complex sonorities of vocal improvisors we find sub-harmonics, biphonation, sudden onset of irregular phonation (possibly deterministic chaos) interspersed with more periodic windows and sudden frequency jumps (register changes). We argue that nonlinear phenomena, well-known in voice pathology, play an essential role in modern artistic vocalizations. In the following sections we will discuss bifurcation analyses, potential physiological mechanisms, issues relative to reproducibility, and their musical relevance.

A. Bifurcation analysis

According to the theory of nonlinear dynamics, all systems feature a limited set of qualitatively different dynamical behaviors. In this paper we document how this applies to sound production of the voice, in particular for solo vocal improvisations by performers using their voices for artistic sound production. The attractors relevant to the physical description of oscillatory systems are limit cycle (related to periodic oscillation), folded limit cycle (related to subharmonics), torus (related to two frequency oscillation) and chaos (related to highly irregular, aperiodic and noise-like behavior).

Transitions between different dynamic regimes (i.e. different attractors) are predicted to occur even for slowly varying system parameters like pitch, formants, subglottal pressure or the varying interaction with supraglottal tissue structures. A comprehensive visualization of transitions can be achieved by bifurcation diagrams[42] which display different dynamical behavior depending on one or two varying system parameters. Such diagrams were calculated for a simplified two-mass model of vocal folds[67] and continuum models.[68] Furthermore, bifurcation diagrams were measured for excised larynx

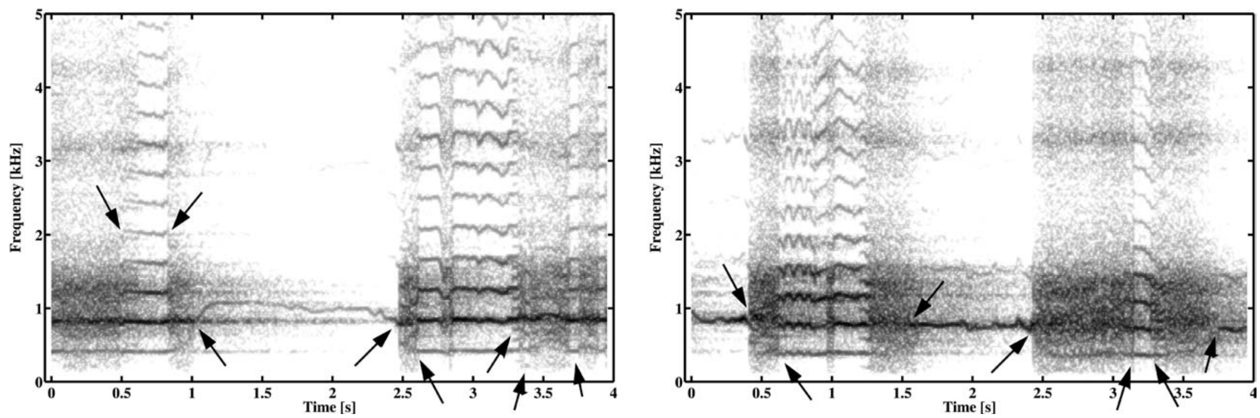

FIGURE 6. Recurrent instances of abrupt transitions from regular phonation to subharmonics and irregular phonation (arrows) within the same vocalization sequence (Sample from solo vocal improvisation *entre nosotros - epitafio a las ballenas* by the vocal improvisor Fatima Miranda.[63]

experiments[69] and analyzed for a voice with unilateral paralysis.[70]

Here we use time-frequency plots (spectrograms) as spectral bifurcation diagrams.[54–56] In contrast to bifurcation diagrams obtained from mathematical models or experimental setups, where single system parameters can be varied, we have no direct measurements of the varying system parameters in *in vivo* multi-tone complex sonorities of vocal improvisors. Thus in spectral bifurcation diagrams, time is considered a "control parameter" of the system.

There are a few hints on changing parameters of pitch, formants, and subglottal pressure due to different shading of spectral lines and noiselike elements in the spectrographic displays. Thus we can speculate about the physiological mechanisms that determine the vocal outputs.

B. Physiological mechanisms

We suggest that formant induced transitions might play a role in the production of sub-harmonic and biphonic sequences. In Fig. 4 we show an example of a formant induced transition for a harmonic phonation to an oscillation with sidebands. Thus a second frequency modulates the initial harmonic output during formant matching which can be observed as sidebands in the spectrogram. With respect to nonlinear dynamics nomenclature, such transitions might be called secondary Hopf bifurcations. They change the behavior of the system from a limit cycle oscillation to a toroidal oscillation–a torus in phase space. The dominant time varying formant seems to play a crucial role in destabilizing the glottal oscillator coupled to the vocal tract. Similarly, in Fig. 5 we give an example of a formant induced bifurcation for a harmonic vocal output to subharmonic oscillation. This conclusion is supported by previous model studies in simplified models for source-tract interaction. Sub- and supraglottal resonances were found to be relevant for high-pitched phonation and, moreover, biphonation.[71]

Second, it has been reported that sub- and supraglottal oscillators (and resonance factors), such as ventricular fold phonation, epiglottic and arytenoid cartilage, can contribute to a variety of complex modes of phonation.[72]

Third, another mechanism that can induce transitions of dynamical behavior is vocal fold asymmetry. Left-right asymmetries and anterior-posterior asymmetries facilitate subharmonic oscillation, biphonation and even chaotic vibration.[17,24,69,73]

Fourth, excessive subglottal pressure, increased stiffness of the vocal fold mucosa, or reduced prephonatory glottal shape (phonation neutral area) leading to chaotic vibrations have been identified in a recent study of a simplified two-mass model, even for a symmetrical vocal fold configuration.[47] Excessively high airflow with a lax laryngeal posture has been implicated in the simultaneous production of subharmonics and deterministic chaos.[74] We argue that vocal improvisors exploring the full range of vocal abilities are able to use exceptional, but not

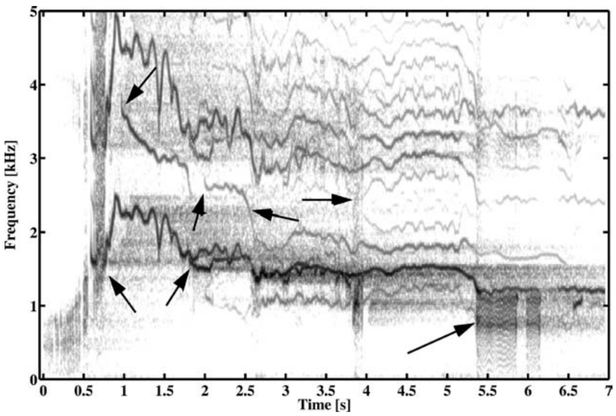

FIGURE 7. Female glottal whistle with biphonation and triphonation. Final segment with triphonation with two glottal whistle and third, vocal fry–like oscillator (Sample from solo vocal improvisation *Signals* by the vocal improvisor Anna Homler.[62]

pathological, methods to induce multi-tone complex vocal sonorities such as (multiple) subharmonics, biphonation and irregular aperiodic sound signals. (see Fig. 3 and 6).

Fifth, we argue, that vocal improvisors can use glottal whistles to produce complex sonorities. The term 'glottal whistle' describes vortex-generated sound with partially adducted glottal or supraglottal constrictions that may also feature slight vocal fold vibrations (vortex-induced fold vibrations). We suggest that these biomechanic or aerodynamic vibrations may be produced at different locations simultaneously within the glottis. The subglottal airstream as the driving force could facilitate one possible coupling between these different oscillators. Thus, biphonation or triphonation could occur due to several interacting oscillators: left versus right vocal fold, anterior versus posterior parts of the vocal folds, glottal versus supraglottal vibrating structures, or vortex-induced vibrations. Moreover, typical formant frequencies in the range of several kHz, thus matching the pitch of the glottal whistle, could either stabilize biphonation or induce transitions to oscillations with sidebands or even irregular behavior.[74] The highly variable time course (melody) shown in Fig. 7 suggests the lack of accurate control mechanisms. The melody may thus result from pressure/flow regulated behavior or from relaxation behavior of tissue stiffness.

C. Reproducibility, intention, and control

Resulting from personal performance experiences, the development of special training programs of amateur and professional voices, and the acoustic analysis of hundreds of sound samples of vocal improvisors, we claim that singers are able to use nonlinear phenomena intentionally. We argue that the above mentioned physiological mechanisms ensure reproducibility in a musical context. These mechanisms include vocal tract resonance tuning, subglottal pressure adjustments, or voluntary desynchronization of vibration modes using asymmetries. Despite variation in minute details of bifurcations to subharmonics, biphonic or irregular segments (see Fig. 5 and 6), the vocal sonorities can be produced in artistically controlled methods. In contrast to pathological phonation where nonlinear phenomena occur accidentially, certain vocalists are able to control the recurrent production of complex sonorities. Musically, control is important for sound output: by changing perceptually robust variables over time, an intended affect, emotion or meaning can be produced.[75,76] Next, as many performance techniques of vocal improvisors may last the duration of a performer's career or even life-span, it is obvious that these techniques are not necessarily aberrent behaviors to be avoided,[77] but rather can be physically and spiritually beneficial.[78,79]

D. Musical relevance

The insight provided by nonlinear dynamics to the understanding of complex musical vocalizations can offer valuable information about an instrument with no levers, buttons or strings – the voice. This type of analysis offers the identification of a phenomenon with a class and a process. For example, biphonation is identified as a torus that appears via a secondary Hopf bifurcation.

Historically, sonorities of vocal improvisors are described by a combinatorial multiphonic framework which has its origin in the broad linguistic classification. This scheme identifies the degree of voicing that appears within speech or song, traditionally identified as either voiced or unvoiced.[35,80] 'Voiced' refers to mostly harmonic outputs produced within the laryngeal framework, whereas 'unvoiced' refers to both harmonic and inharmonic sounds produced at different locations superior to the larynx produced by manners such as stops, fricatives, approximants, whistles or buzzes. Many sonorities of vocal improvisors feature the perception of two or more identifiable tones, often the result of multiple source components.[30] As a result, numerous categories have been developed that combine 1) voiced sound with another voiced sound ('voiced-voiced'); 2) voiced sound with an unvoiced sound ('voiced-unvoiced'); 3) unvoiced sound with another unvoiced sound ('unvoiced-unvoiced').[35]

In this paper, we integrate this combinatorial multiphonic framework with the theory of nonlinear dynamics to describe archetypical phenomena – subharmonics, biphonation, and irregular aperiodic phonation. We give ideas for linking physiological mechanisms with nonlinear phenomena in a few typical multiphonic behaviors within the combinatorial framework. Thus, we suggest a robust musical terminology which merges production-related terminology with nonlinear dynamics.

Within the voiced-voiced category we argue that nonlinear phenomena could occur due to glottal asymmetries (left-right or anterior-posterior), desynchronization of other complex glottal vibratory modes and coupling of phonation with supraglottal vibrations (e.g. the ventricular folds). Within the voiced-unvoiced category, which includes vocal fold oscillation with unvoiced supraglottal oscillation or friction, we argue that all nonlinear phenomena can be expected for coupled glottal and supraglottal unvoiced oscillation, such as glottal phonation with lip buzz. The combination of vocal fold oscillation with frication should lead to irregular or turbulent outputs as the aerodynamic oscillators are thought to have a strong effect when glottal phonation is combined with pharyngeal frication. Within the unvoiced-unvoiced category, which includes tongue with oral cavity frication or labial whistle with pharyngeal articulation, we can define subgroups according to the manner of (un)voicing, such as unvoiced oscillation with unvoiced oscillation, unvoiced oscillation with unvoiced fricative, or unvoiced fricative with unvoiced fricative that indicate relative amounts of pitchedness versus inharmonicity. The first subcategory of 'unvoiced oscillation with unvoiced oscillation' is associated with limit cycle oscillations, subharmonics and biphonation. Both other subcategories are more linked to irregular or turbulent behavior.

One readily-available tool relevant for sound analysis is the spectrogram. In the context of acoustic chaos spectrograms are called spectral bifurcation diagrams.[54] When time is considered as a control parameter, they are also termed 'visible speech'.[56] Spectrograms may also contribute to the training and treatment of desired or aberrant voice signals as windows of visualization. When combined with information regarding airflow, laryngeal posturing and tension, etc., we propose to use them similar to instrumental fingering charts (standard pedagogical tools for producing nonstandard extended complex instrumental sonorities[81]). Through the identification of specific aerodynamical and physiological parameters, approximate scales within a parameter space can be introduced. In this way, multiple parameters can be continuously varied between minimal and maximal values, such as the pitch/rhythmic axis found in common-practice music. This procedure may be referred to as scalability,[35] and suggests that what was formerly considered extraneous acoustic/physiologic elements now attain a greater role during the production of multi-tone complex musical signals.

For the clinician and performer, if (control) parameters encompassing multi-tone complex phonation can be described with scales, then the efficacy of training and treatment might attain significant benefits. For contemporary compositional practice, at least two benefits may be proposed. First, by using these parameters as scalar properties (between minimal and maximal values), artistic quality is enhanced by offering coherence of compositional procedure across multiple parameters. Second, regarding multi-tone complex sonorities and extended nonstandard gestures, the heightened emphasis of these parameters might offer exciting additional musical outputs worth continued artistic exploration.

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