Article:

Acosta Martínez, Gerardo and Daffern, Helena orcid.org/0000-0001-5838-0120 (2025) The Role of Vibrato in Choral Singing:A Systematic Review. Journal of Voice. 847.e21-847.e39. ISSN 0892-1997

https://doi.org/10.1016/j.jvoice.2022.11.004

The Role of Vibrato in Group Singing: A Systematic Review

Gerardo Acosta Martínez, and Helena Daffern, *Heslington, United Kingdom*

Summary: Introduction. Arguably one of the most controversial features of the singing voice, especially in a choral context, is the phenomenon of vibrato. Numerous pedagogical articles, mostly written by experienced choral singers or directors, discuss the importance of vibrato, sharing anecdotal insights about its control (often advocating reduction) in choral blend and vocal health.

Objectives. This systematic review aims to identify the main questions posed in the empirical study of vibrato during group singing, and how they have been addressed to date through empirical investigations.

Methods. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses was employed for this review. The review team consisted of the two authors. A data extraction form was designed to capture information about the participants (including age, gender, music and singing experience), study methods, experimental procedures, outcome measures, and statistical findings.

Results. Seventeen studies were included in the review and revealed that (a) relatively few empirical investigations have studied vibrato in vocal ensembles; (b) the majority focused on vibrato production rather than perception; (c) methodological approaches include Synthesis, Multi-track recordings, Stereo/Binaural recordings, and Lx/Contact recordings; and (d) the studies focused on the main themes of Adjustment, Identification, Interaction, Intonation, and Style.

Conclusion. With the current body of literature, it is not possible to draw general conclusions around vibrato behavior during group singing. However, the review highlights the main subareas of interest and valuable methods which have been established and through which future research can collectively shed further light on the role of vibrato in choral singing.

Key Words: Vibrato−Choral−Singing−Blend−Systematic−Review.

INTRODUCTION

The singing voice is a complex instrument that can create a wide variety of sounds encompassing many musical styles and conveying complex emotional expressions.[1−4] Among these, arguably one of the most controversial features is the phenomenon of vibrato—an oscillation of the fundamental frequency in the singing voice that has been studied from perspectives of physiological aspects, acoustic factors, and psychoacoustic attributes. In 1931, Seashore sought to define vibrato from a psychoacoustic perspective, identifying "a periodic pulsation, generally involving pitch, intensity, and timbre" adding "which produces a pleasing flexibility, mellowness and richness of tone,"[5] and also "an interesting, warming vocal quality, full of life and sparkle, giving a deviation from a perfectly steady tone which has emotional and artistic value."[6]

A review by Sundberg in 1994[7] provided a comprehensive study of the four acoustical attributes of vibrato—*extent, rate, regularity*, and *waveform*—and defined it as "a fundamental frequency undulation at a rate of five to seven undulations per second and an extent of about ± 1 semitone." Additional studies have reported parameter values within this range, although there is also evidence of slower rates of 4 Hz (starting to be perceived more as a *wobble*) and faster rates of 8 Hz (as found in opera singers[8]). Regarding the physiological aspects, the exact mechanisms of vibrato production are still debated. Research has shown that there exists laryngeally mediated vibrato, characterized by the dynamics of the cricothryriod muscle; and abdominally mediated vibrato, affected by the amount of subglottal pressure.[9] A more extensive description by Hirano et al.[10] provided four major aspects that play roles in the physiology of vibrato—including neural mechanism and aerodynamics in the voice.

Currently voice research has widely studied the production and perception of vibrato through measures of acoustic parameters, loudness, mathematical models, synthesis, and listening tests.[10−20] On the other hand, numerous pedagogical articles, mostly written by experienced choral singers or directors, discuss the importance of vibrato, sharing anecdotal insights about its control (often advocating reduction) in choral blend and vocal health.[21−26] For instance, in the article *Good Vibrations: Vibrato, Science, and the Choral Singer*,[23] the author described that "Experts offer a wide range of view points regarding vibrato in choral singing, from those who believe in a free, soloistic vibrato to those who advocate a minimal vibrato or even straight tone. [...] Given the polarity of these opinions, with healthy vocal technique and sound quality in the balance, it behooves choral conductors to learn as much as possible about the phenomenon of vibrato."

The challenges for research imposed by vibrato are multiplied singer-fold in the context of choral singing. This is caused by the fact that studies need to observe not one but multiple vibrato oscillations at once, and as Neubauer put

Accepted for publication November 2, 2022.

From the AudioLab - University of York, Genesis 6, Innovation Way, Heslington, York, United Kingdom.

Address correspondence and reprint requests to Gerardo Acosta Martínez, University of York, Genesis 6, Innovation Way, Heslington, York, YO10 5DQ, United Kingdom. E-mail: gerardo.acosta@york.ac.uk

Journal of Voice, Vol. 39, No. 3, pp. 847.e21−847.e39

0892-1997

https://doi.org/10.1016/j.jvoice.2022.11.004

it: “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.”[3] Furthermore, empirical research on choir acoustics faces numerous practical challenges, including for instance, how to isolate the individual vibrato contours of participants from the combined sound of the choir for analysis. New technological developments have shown the ample potential of tools and analyses needed to address some of these problems.[27−32]

Although certainly not abundant, existing literature related to vibrato in choral singing unveils scientific findings[33−37] that could support singing and choral pedagogy and performance practices. Examining empirical research to identify findings and approaches to inform our understanding of vibrato and choral singing could highlight areas for further enquiry to advance, and hopefully encourage, best practice in choral performance, pedagogy, and research.

This systematic review aims to identify the main questions posed in the study of the relationship of vibrato and choral singing, and how they have been addressed to date through empirical investigations. The objective of the review was to assess the role of the production and perception of vibrato in choral singing in the published scientific literature. The research questions were: Are there common findings associated with vibrato in the current choral literature? Is existing empirical evidence sufficient to support common recommendations regarding vibrato as contributing to blend and music style in choral practice?

MATERIALS AND METHODS

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)[38,39] was employed for this review following the procedure described in the following subsections. The review team consisted of the two authors of this study (GAM, HD), and methods and procedures were documented in advance in a bespoke protocol.

Eligibility Criteria

The following criteria were defined for research to be included in the review:

1. Studies reporting data or results of vibrato production or perception such as extent, rate, regularity, waveform, loudness, theoretical models, synthesized systems, correlation metrics, or other perceptual measures
2. Studies investigating group singing in real-time (more than one voice involved)
3. Published empirical research articles, including full papers in conference proceedings
4. Studies written in the English language.

Only studies that met all of the above criteria were included in the review. Therefore, articles that dealt broadly with the choral voice but only studied voices singing in solo conditions were excluded. Likewise; review articles, abstracts in conference proceedings, and unpublished studies were also excluded. No exclusion was defined regarding participant characteristics, time or place of publication.

Search Strategy

A preliminary search was conducted as described in the Centre for Reviews and Dissemination guidance.[40] The electronic database used for this was Scopus, using terms and synonyms related to group singing and vibrato. Then, a four-step approach was devised for a thorough search strategy as described below.

Firstly, a refined and detailed electronic-database search strategy was developed based on the PRESS guidelines[41,42] to optimize the identification of records with minimal irrelevant results. The search was developed by GAM and reviewed by HD. We used three databases (Scopus, Medline, and PubMed), and an adaptation of the following main string chain for each of the sites’ operators:

1. *vibrato OR “pitch variation” OR “pitch fluctuation” OR “fundamental frequency oscillation” OR “fundamental frequency variation”
2. sing* OR voice* OR vocal* OR phonation
3. chor* OR choir OR unison OR duet OR trio OR quartet OR quintet OR “group singing” OR “ensemble singing”
4. 1 AND 2 AND 3.

No additional limits were used (eg, dates of coverage). Additionally, the full search query for PubMed is presented in Appendix A.

Secondly, out of the records collected for inclusion through the above search, we identified the key journals for scanning their online databases. Thirdly, we looked for other relevant web sources (eg, handsearch in Google Scholar using relevant terms as described above). Finally, we considered the referenced literature of each of the articles included in the review. The last search was run on June 13, 2022.

Study Selection

The study selection was performed independently by the members of the review team to reduce error and bias, and to confirm eligibility of the records. The screening of the articles took place in two main phases: An initial screening based on title and abstract; then a more detailed screening where articles were assessed in full to determine inclusion or exclusion. Results from the two reviewers were compared for consistency. No discrepancies were found.

Data Synthesis

For the articles included after full assessment, a data extraction form was designed in a LaTeX tabular to capture information about the participants (including age, gender, music and singing experience), study methods, experimental procedures, outcome measures, and statistical findings. The high variation of participant characteristics, design, and methods between the experiments required us to categorize studies based on key, general concepts, and their objectives and aims. As such, results are presented using a qualitative synthesis of data and no meta-analysis was performed.

RESULTS

Figure 1 shows the PRISMA flowchart of the search strategy results. The search of Scopus, PubMed and Web of Science databases provided 64 records, whilst key journals, other sources, and reference lists provided 75 records. The two most recurrent journals from the database search were *Journal of Voice* and *The Journal of the Acoustical Society of America*. After removing duplicates, we identified a total of 112 records, from which 81 were assessed in more detail for eligibility. Seventeen studies were included in the qualitative synthesis, and 65 studies were excluded with the reasons indicated in the PRISMA flowchart—some satisfying more than one reason for exclusion.

Characteristics of Included Studies and the Participants

Table 1 shows the list of studies included in this review.[43–59] We identified three main categories: Studies of vibrato production, studies of vibrato perception, and studies combining the two. The number of participants per study ranged from 2 to 48. The study by Coleman[43] had the lowest number of participants—two, a tenor and a baritone singing in duo—which he defines as the simplest possible case through which to study group singing. And the study by Erickson,[49] a listening test study, had the highest number with 48 participants.

The reporting of gender or biological sex at birth was ambiguous and diverse, with both single and mixed gender/sex studies. Five studies[44,49,51,53,57] reported no information regarding biological sex or self-identified gender of participants. The term gender will be used as most representative of studies from this point. Reports of age were very uncommon, with only five studies[45–47,52,59] reporting this information. Most reported age in year ranges, although a few of them also reported age using the mean and standard deviation (SD). Overall, the age range of studied participants was from 14 to 55 years old.

Almost all studies reported information regarding vocal training of participants. To standardize, we categorized this as trained or untrained, even though some authors reported further details such as graduate level or years of training. Information about the experience of participants shows that all studies of voice production had singers with some kind of vocal experience—some of them were choral singers, others students, and others professional singers. The exceptions were perceptual studies, which considered experienced listeners as well as participants with no reported musical experience.

Methodological Approaches

The review reveals that researchers have utilized a number of common tools and methods in order to study the effects and behavior of vibrato in choral singing. We identified four main approaches to the methodologies: Synthesis, stereo/binaural recordings, multi-track recordings, and contact-microphones/electro-laryngograph (Lx) or electroglottograph (EGG) recordings. Figure 2 shows a pie chart of the results, and the data for each record is presented in Appendix B.

Vocal synthesis provides a controlled and isolated environment from which to study singing voice characteristics.

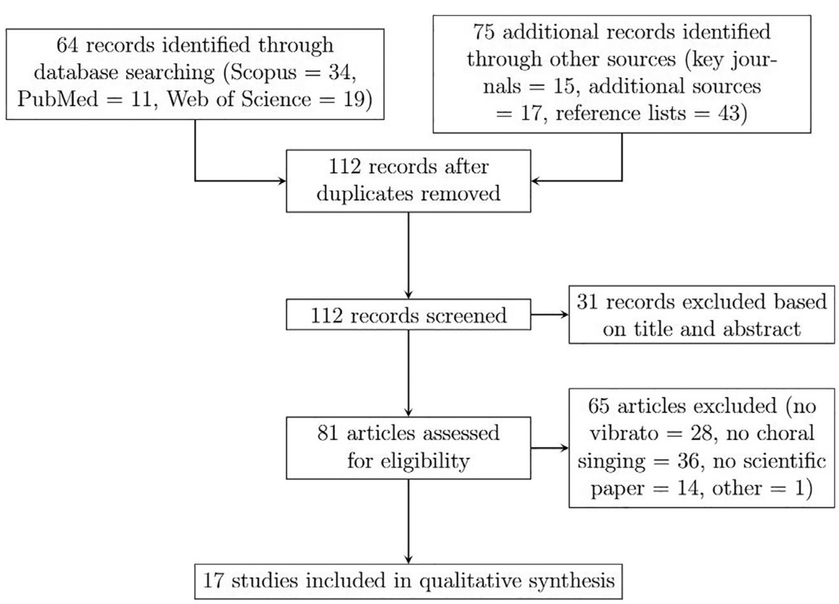

FIGURE 1. PRISMA flowchart.

TABLE 1.
Included Studies in the Review and the Descriptive Characteristics of Participants

Study	Type	Participants				
		N	Gender	Age (yr)	Training	Experience
Coleman 1994	Pro	2	M	NR	T	PS, OS
Culling & Summerfield 1995	Per	3, 4	NR	NR	NR	NR
Daffern 2017	Pro	4	F, M	19 to 21	T	SS
Dai & Dixon 2019	Pro	20	F, M	20 to 55	T	CS
Dromey et al. 2003	Pro	15	F	19 to 28	T	SS
Duncan et al. 2000	Pro	4	F	NR	NR	PS
Erickson et al. 2012	Per	48	NR	NR	T, UT	E, I
Goodwin 1980	Pro	30	F	NR	T	CS
Jers & Ternström 2004	Pro	16	F, M	20 to 32	T	CS
Le Beux et al. 2011	Pro	4	NR	NR	NR	NR
Mann 2014	Mix	30	F	19 to 22	T	CS, SS
McAdams 1989	Per	10	NR	NR	T, UT	I, AM
Reid et al. 2007	Pro	26	F, M	NR	T	PS, OS
Rossing et al. 1987	Pro	7	F	NR	T	PS, CS
Sacerdote 1957	Pro	≈15	F, M	NR	NR	CS
Ternström et al. 1988	Pro	NA	NA	NA	NA	NA
Ternström & Sundberg 1988	Pro	18,17	M	NR	NR	CS

Notes. AM = amateur musicians, CS = choral singers, E = experienced, F = female, I = inexperienced, M = male, NR = not reported, OS = opera singers, Pro = production, Per = perception, PS = professional singers, SS = singing students, T = trained, UT = untrained.

It is used both directly studying synthesized signals with vibrato, and as a stimulus in singing voice experiments. Stereo and binaural recordings have also been used and can be useful in studies which either deal with few subjects or are interested in analysis where isolated signals are unessential (for example perceptual testing). Multi-track recording was the most used method in the records from the review (Figure 2). Here we use the definition of multi-track recordings from studio techniques, which means to record individual signals either *independently* (using pre-recorded stimuli as a "backing track") or *simultaneously* (as in live performance of multiple singers with some method to capture isolated voices with minimal bleed from other singers). This method is useful for acquiring individual signals (to some extent in the case of simultaneity) from ensembles with large numbers of participants, and also for prerecorded signals that are later used as stimuli.

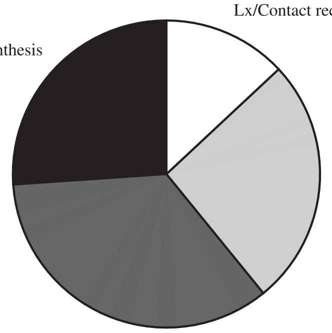

FIGURE 2. Proportions of the methodology approaches of studies included in the review.

Another approach to capturing isolated signals from individuals as they sing together is to use contact microphones and Electrolaryngograph (Lx) recordings. Both rely not on air vibrations but direct-contact measurements. Lx a noninvasive method that measures the vibratory cycles of the vocal folds during phonation via electrodes placed in the front of the neck. Up to now, Lx was utilized in only one of the studies on vibrato and choral singing.[45] Research on choir acoustics shows, however, this tool offers a practical solution to isolate and study directly the individual contributions of each voice within ensembles of high number of participants.[31,60]

The above methods are not employed exclusively, and often studies used a combination of them in a single experiment. The study by Ternström and Sundberg,[58] for instance, combines the four methods in a set of experiments that aimed to analyze the difficulty of intonation using different vowels and different harmonic intervals, with the hypothesis that vibrato facilitates intonation due to reduction of beats and roughness. For this they first used (1) a 10-second long synthetic stimuli of sung vowels under different conditions (eg, vibrato), then (2) sung stimuli recorded with Sennheiser binaural microphones, (3) a dummy head in a Revox stereo tape recorder, and (4) contact microphones "fastened to the throat below the larynx" for the singing participants.

The included study by Sacerdote[56] did not explicitly state which method was used to acquire the choral signals that are described in his article's last experiment: A female choir singing in unison and a monodic choir of "around 15 men." However, given the graphs and descriptions presented (as well as the date of the study) we inferred the author recorded

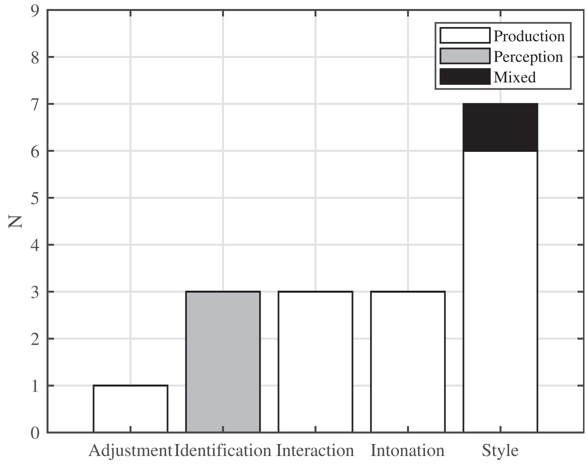

FIGURE 3. Thematic categories of studies included in the review.

the signals from the choir singers using a single microphone or a stereo setting.

Thematic Categories of Study Objectives

The main aims/objectives each study sought to accomplish (Figure 3) were categorized to consider similarities across the research. In total, five thematic categories were established as described below. We note that this categorization provides a perspective of the landscape of the research overall, but naturally some studies are extensive and their objectives may overlap between categories. (Full data in Appendix B, Table B.2.)

Adjustment: Intrapersonal Adaptations and Vibrato Matching

One of the included records studied adjustment and adaptation of vibrato.[47] This category deals not with the complex interactions of multiple voices with each other, but with the level at which individual voices can intrinsically alter and match their properties to another or other voices. This was studied using an external, prerecorded stimuli that a singer attempts to match or adapt to. Dromey et al. studied the acoustic characteristics of singers who attempted to match vibrato stimuli with different rates (slow and fast). Results indicated that trained singers were able to adjust their vibrato to the external stimuli, and the study raised the question of whether this is also possible in the long term and without external stimuli.

Identification: Auditory Isolation of Voices

The ability to distinguish and identify individual voices within a sound (Auditory Segregation) was the main objective of the three studies in this category. Erickson[49] performed listening tests to find the effect of vibrato on the perception of two simultaneous singers, the hypothesis being that voice pairs with vibrato would be easier to segregate, particularly at higher pitches. This prediction was derived from the previous studies by McAdams and Culling[44,53] showing that frequency modulation (FM) increases *prominence* or source identification within a complex sound, regardless of coherence and “differences in the pattern of that modulation.”

Participants of Erickson’s study were both listeners with experience in music and singing, and listeners with no experience in any activity related to music. The task consisted of hearing two sets of synthesized singing stimuli with different characteristics, one with a pair of voices singing simultaneously with vibratos 180° out of phase, another without vibrato. The study provided no comprehensive conclusion as authors reported that vibrato “significantly improved listener’s perceived ability to hear two simultaneous voices” at some combination of pitches and formants, but no improvement at others. The discrepancy between this and the findings from McAdams and Culling could be related to additional timing onset conditions in Erickson’s study.

Interaction: Interpersonal Relationship of Singing Voices

Three studies of the review analyzed the inter-participant interaction of voices in a group singing situation.[45,48,59] In this category, the aim transcends the assessment of individual properties of the voice. Rather, these studies focus on the degree to which singers can adapt or modify their voices based on their interactions with each other as they sing together. The three articles introduce interesting concepts in group singing such as vibrato synchronization, generally referring to a form of:

- *coherence*, “the measure of the state in which two signals maintain a fixed phase relationship with each other”
- *phase-locking*, “the mutual interaction among oscillators by which the phase difference between any two oscillators is fixed”[61];

which form the basis for studying vibrato behavior in multiple voices. The study by Sacerdote, in 1957[56], hypothesized about the possibility of vibrato synchronization in choirs, but experimental evidence and measurements would only come in future studies.

In the study by Duncan et al.,[48] the authors used CD stereo recordings from internationally renowned singers singing in pairs. The chosen piece of the recordings allowed the authors to extract the vibrato oscillations from musical notes sung under different conditions (solo singing and simultaneous singing) and also different pitches and durations. Results indicated that it is possible that singers are able to adapt their vibrato in order to achieve synchronization. This gives rise to patterns of interaction such as in-phase synchronization, a positive correlation; or anti-phase synchronization, a negative correlation. This last case means the extent of vibrato would have inverted amplitude

TABLE 2.
Overview of Procedures, Measures, and Findings Related to Vibrato

Study	Experimental Procedures	Metrics and Outcomes	Statistical Findings
Coleman 1994	Two pieces with different styles Singers performed in a large church Recorded with contact microphones Additional B&K microphone at 1 m	LTAS, SPL Frequency analyses	NR
Culling & Summerfield 1995	Two experiments on vowel masking 400 ms & 2 s synthesized stimuli Different f_o, sinusoidal 6.3 Hz FM Coherent and incoherent modulation	Vowel identification Threshold of identification	Repeated measures covering modulation coherence, maskers, and background vowels
Daffern 2017	Singers recorded together Two pieces of their repertoire Additional bespoke piece Use of Lx and close microphones	Vibrato extent of notes Vibrato waveforms	Pearson correlation for the vibrato portion of the final note ($P \leq 0.05$)
Dai & Dixon 2019	Two contrasting pieces selected Each piece sung ten times Three conditions of monitoring Recorded in acoustically isolated rooms	f_o Mean, median, and SD of note transients	NR
Dromey et al. 2003	Twelve singers recorded vowel samples Eight singers attempted to match Recordings made on sound booth Head mounted microphone AKG C420 Fast and slow rate stimuli	Vibrato waveforms Rate, extent	Several tests using ANOVAs and t-tests with Bonferroni corrections
Duncan et al. 2000	Data were commercial CD recordings Three recordings of Delibes' Flower Ten pairs of duet notes selected Results of one long pair of notes Solo and duet singing analysis	Mean vibrato rate Vibrato waveforms	NR
Erickson et al. 2012	Paired synthesized stimuli Different combinations of vibrato Vibrato cycles 180° out of phase Stimuli played on Sennheiser H265	Perceptual measures 0 to 50 point scale	Significant results for the effect of vibrato ANOVAs and Bonferroni corrections ($P < 0.001$)
Goodwin 1980	Singers produced sustained notes Solo and blend conditions Headphone monitoring for both Recorded in a soundproof room	Vibrato waveforms	NR
Jers & Ternström 2004	8-bar canon by Praetorius Performed in unison Males and females 1 octave apart 16-channel recording Miniature electret microphones Sung at normal and slow tempo	f_o contours	NR
Le Beux et al. 2011	Real time formant synthesizer Graphic tables & joysticks Alta trinita beata polyphony	f_o graphs	NR
Mann 2014	Singers prepared two pieces Mozart's *Laudate Dominum* Rutter's *Thy Perfect Love* Solo and choral modes Recorded using Zoom H2 Accompaniment via headphones	Vibrato rate, extent and duration means Perceptual questionnaire Descriptive terms	Significant difference between modes using three-way ANOVA on vibrato duration ($p < 0.05$)
McAdams 1989	Concurrent vowels at three pitches Six stimuli permutations Modulated, unmodulated conditions Presented at 75 dBA Neve console, AKG K242 earphones	SD, standard error Linear scale of salience of a given vowel /a/, /i/, or /o/	Two-factor ANOVA of pitch and vowel judgement
Reid et al. 2007	Singers individually recorded Solo and choral mode, different music	LTAS, SPL Vibrato extent and rate	NR

(*Continued*)

TABLE 2. (*Continued*)

Study	Experimental Procedures	Metrics and Outcomes	Statistical Findings
Rossing et al. 1987	Program recorded binaurally Anechoic room Choir and solo modes	SD of f_o	NR
Sacerdote 1957	Monodic women's choir Monodic men's choir Measurements singing plainsong	Vibrato graphs	NR
Ternström et al. 1988	Various simulation of f_o contours Sine waves, noise generators Filters with vibrato bandwidth	Vibrato waveforms	NR
Ternström & Sundberg 1988	Two experiments in anechoic room Synthesized stimuli over loudspeakers Sung stimuli over Sennheiser HD 414 Presence and absence of vibrato	SD of f_o (SF0)	Effects of vibrato on SF0 ($p \leq 0.01$)

or be 180° out of phase (as in the listening tests of Erickson and Gaskill[49]).

Daffern in 2017[45] reported similar results in an ecological study of a Soprano, Alto, Tenor, Bass (SATB) quartet ensemble through 10 weeks of training. With an ensemble of four singers, this study utilized multi-track and Lx recordings to isolate individual voices. The results provided evidence of both the employment of vibrato as a collective feature potentially contributing to choral blend and its adaptation across multiple sessions as the quartet worked towards a recital performance.

Intonation: Pitch Trajectories and Accuracy

Intonation has long been one of the main features of interest in choral acoustics.[33,62,63] This doesn't come as a surprise given that in choral singing and *a capella* singing pitch accuracy is imperative and complicated as "vocal tuning is completely variable to a fine degree; singers are non fretted instruments."[36] The studies included in this category focused on understanding the role of vibrato on: The intonation precision of choral singers,[58] the intonation of a synthesized choral system controlled by hand movement,[51] and a report of the absence of vibrato in analyses of intonation trajectories from an unaccompanied SATB quartet experiment.[46]

The study by Ternström[58] mentioned above which used voice synthesis and real voice recordings, analyzed the intonation precision of choral singers to a stimulus. The study found that lack of vibrato facilitated the mentioned f_o accuracy.

The conference paper by Le Beux et al.[51] presents a synthesis system for SATB choral singing, where the vocal intonation of each singer could be controlled by four game joysticks. The system allowed users to perform a musical piece simultaneously by varying the micro-intonation (5 to 10 % of a semitone) of their vocal part with the joystick. In this way, a "waving motion" wrist would create oscillatory patterns that were associated with vibrato. The study reports recordings from the authors' performances in the system and a set of graphics illustrating the f_o waveforms. They described the "bass player had on all trials a vibrato in the same order of magnitude as real singers, around half a semi-tone." And the "other players [had] a vibrato of approximately a quarter of semi-tone."

Finally, in the study of intonation trajectories performed by Dai & Dixon,[46] the authors actively reported a lack of vibrato in a singing model of unaccompanied soprano, alto, tenor, bass quartet singing. The experiments consisted of participants singing their parts in different conditions and recording/modeling the intonation trajectories, in which there was no vibrato—at least not even and prominent enough to be modeled. The authors suggest that choral singers avoid vibrato perhaps in their attempt to contribute to blend. The study discusses that "although vibrato is a feature of many singing pitch trajectories, we did not explicitly model it in this work. The use of vibrato is less marked in unaccompanied ensemble singing where the voice does not need to be projected over instrumental parts, and the stylistic goal is for the voices to blend rather than stand out."

Style: Solo Singing, Choral Singing, and the Choral Sound

Seven studies from the review[43,50,52,54−57] focused on stylistic differences of the voice between music genres (e.g. classical, opera, liturgical) and the characteristics that create the *choral sound* or *choral effect*. Sacerdote, in 1957,[56] laid the groundwork in choral singing science exposing the interest in the question of what defines the choral sound. Researchers have been interested in understanding the acoustic properties of *solo singing* versus *choral singing*, which some of the studies here define as *singing modes*, stating that experienced singers are able to use a different type of voice when singing in a solo or a choral context.

One of the earlier studies to measure the phenomenon of singing modes was Goodwin in an experiment[50] that analyzed the spectral characteristics of sustained vowels of sopranos first singing in their solo voice, and next attempting to blend to a prerecorded unison ensemble sound of soprano voices, to yield an alternative choral mode. The results showed the singers employed vibrato reduction in the choral condition alongside other blend techniques such as vowel modification and dynamic level adjustment. In a later study, Rossing et al.[55] extended this research by analyzing Sound Pressure Level, Long-Term Average Spectrum, and vibrato characteristics in four sopranos and one mezzo-soprano singing in solo and choir modes. Regarding vibrato production differences, the study concluded that "the extent of vibrato appears to be somewhat greater in solo singing."

On the other hand, the study by Ternström[57] addressed the subject of choral sound using vocal synthesis of voices signals with different types of FM in f_o. His objective was to replicate the subtle nuances that multiple singers have by using random-noise generators and band-pass filters. The cut-off frequencies of the filters were different—in the ballpark of the commonly accepted vibrato band[7]—so that each one added different components to the sound to emulate the choral effect once summed together. The rationale was that signals that are identical to each other create no "sensation of ensemble" as they would be perceived simply as a single sound with doubled amplitude. This is a key element in choral sound according to the author, which described, "The slight tremor in F [f_o] generally varies in character from singer to singer, especially with regard to the vibrato content."

Overview

In Table 2 we provide a summary of the studies' experimental information—including procedures, metrics, and general findings. As some studies have multiple experiments or analyses, we report only those directly related to the aims of this review.

DISCUSSION

In this systematic review, we investigated the main questions that arise in the study of vibrato in choral singing, and how they have been addressed through empirical investigations. The results of the review, based on our particular criteria, show that (a) relatively few investigations have studied vibrato in vocal ensembles; (b) the majority focused on vibrato production rather than perception; (c) methodological approaches include Synthesis, Multi-track recordings, Stereo/Binaural recordings, and Lx/Contact recordings; and (d) the studies focused on main themes such as Adjustment, Identification, Interaction, Intonation, and Style. Furthermore, the review showed that vibrato has an important impact in choral singing from both production and perception perspectives, and that there is evidence of singers adapting/synchronizing vibrato in choral conditions.

Summary of Evidence

Seventeen articles have been identified as investigating vibrato and singing voice in the choral context. But perhaps more important than the volume was the heterogeneity of the findings. From a meta-analysis perspective, findings from 17 articles could yield acceptable data to conduct informative statistics, but given our qualitative synthesis results, we found that the overall metrics and method variations prevent this; particularly considering the perceptual studies, in which no agreement currently exists for studying the degree of choral blending and vibrato effects. Whilst it is possible to narrow our review criteria, this would reduce the relatively small number of sources considerably, and potentially neglect valuable contributions to the field.

The number of participants in the studies had high variability, across both production and perception experiments. In the case of repeated measures, studies such as Coleman 1995 have assessed a pair of singers as satisfying the choral context studied in this review. For statistical power, an adequate amount of vibrato samples can be obtained by either collecting multiple takes of vibrato singing within participants, or also by having multiple singers, as the case of Mann 2014.[52] On the other hand, the study by Duncan et al. also studied duo singing with combinations of four participants. This allowed for the data collection of different duo combinations to study whether vibrato behaviour could favor a specific pair of singers; an analysis that could be extended to studies with more participants. Likewise, the longitudinal study by Daffern included only four participants, where one of the aims was to analyze possible changes in the level of singers interaction over time and rehearsals. For perception studies, the study by Culling & Summerfield had three participants for an experiment, and four for a subsequent within the same article; numbers that could be considered low although the listeners were highly experienced in the area.

Potential differences in treatment of vibrato parameters across vocal ranges during choral singing has been touched upon but not thoroughly explored. In the included study by Rossing et al. 1987, he found that vibrato extent tended to be higher in solo singing; and in his early paper in 1986,[64] he studied the same conditions of choral singing and solo singing in male singers, and provided no findings regarding vibrato production (reason why the study was not included in this review). Research has indicated potential differences in vibrato characteristics across voice classes such as soprano, alto, tenor, or bass. The study by Daffern, for instance, reported differences in vibrato production and synchronization between voice categories as the soprano tended to trigger or "lead" the onset of vibrato in other voices. Also, descriptive differences in vibrato were observed, for instance, between the soprano (more vibrato) and the bass (less vibrato) of the quartet. This could suggest that voices can have different roles of vibrato behaviour depending on the frequency range. Seashore has stated that "No great violinist of today plays without a vibrato,"[5] while no such statement was made regarding double bass playing. Likewise, in contemporary music, producers mostly advocate a stable or "tight" low-end sound from electric basses to provide a solid ground for the higher-pitched instruments to ornament. In short, the role of frequency range and vibrato production in choral singing is something that could prove beneficial to study particularly from a perceptual perspective.

We note that only five production studies report the age of participants for production studies. The age of choral singers could have research implications as additional studies have reported differences in vibrato behaviour of singers over time and choral training. A study by Howard[65] performed a longitudinal study of three female choristers during puberty concluding there was an "improvement" in vibrato, among other vocal parameters of the voice. The variation of vibrato parameters, however, was not reported. On the other hand, Berghs et al.[66] studied the effects of age on voice parameters from choral singers. Because of the wide range of ages the study wanted to address, rather than a longitudinal approach, the authors chose a comparison of a population of singers from a choir in Netherlands that ranged from 20 to 60 years old. They recorded and analyzed the vocal parameters and divided them into age categories for statistical analyses between male and female subjects. The study infers that changes in the acoustic characteristics are associated with age as the chosen choral singers shared similarities in their training and accustomed singing practices. The SD of vibrato amplitude across participants was "moderately" negatively correlated with age in females but not in males. However, participants, in subjective questionnaires, commented that "in their experience vibrato control is one of the main consequences of more technical skills over the years, gained by studying and singing regularly in vocal ensembles". These two studies were excluded from the formal review given that, although their findings support insights of age and gender in choral singers they don't meet the criteria of reporting measurements taken in a choral context. However, they do illustrate the relevance of reporting age, training, and experience characteristics for future studies.

Production and Perception

Through systematic inspection, there is common agreement between the production studies to report findings using the well-known vibrato parameters rate and extent. From the 17 studies, six of them used at least one of these parameters.[45,47,48,52,54,67] In future work, vibrato extent and rate reported along with sample size, mean, SD, mid-range, or mid-quartile range would prove useful for cross-study analyses and statistics. Other metrics were sometimes reported with similar phenomena to vibrato such as shimmer and jitter. These, however, are distinct from vibrato and so were not considered in this review. Another agreement between production and perception studies was to report the vibrato waveform.[10] Although not explicitly reporting rate or extent values, some studies showed the trajectories over time of f_o to describe the oscillatory characteristics.

Less than 25% of the studies included addressed vibrato perception in choral singing. Of the four perception studies, three of them analysed identification of synthesized voices and vowels. In this case, the methodologies used vibrato in simultaneous singing, but the central research question was focused on segregation of tones in sound perception more generally. The argument for the inclusion of voice identification and segregation within this review comes back to the Style category of understanding the choral sound. The three studies in this category suggest that vibrato and the coherence of the signals can help to discern that a complex sound is the sum of various voices. This could be one of the reasons why choral directors might advocate for vibrato minimization. The concept of blend in choirs would dictate that the "auditory segregation" of the voices is in fact something undesirable in choral singing, where the real objective is to come up with a fused, cohesive sound in which individual voices cannot be identified.

The remaining study that contained perceptual measures corresponds to a mixed study, where the main experiment was focused on vibrato production, and the perceptual aspect came from questionnaires filled in by the singers immediately afterwards. We emphasize the difference of these measures from those obtained from listening tests. Though both provide useful insights, results show the possibility of more listening tests to complement and consolidate the work done on production—auditory perception being of essential consideration in studying the acoustics of the voice. As a listening study of vibrato puts it, "singing is predominantly a perceptual phenomenon [...] tailored for human perception."[19]

Review of Common Methods

There were common methodologies used to approach vibrato in choral scenarios across studies, with frequent use of voice synthesis particularly in perceptual studies.[44,49,53] A rationale could be that synthesis facilitates fine control over the FM coherence of coupled vibratos. This allows for purely sinusoidal modulation with perfect periodicity. Although possible to some degree, this would be harder to find in real-voice simultaneous recordings and the phase-locking event might not be independent from changes in other variables, thus the preference to control and isolate coherence through synthesis. However, given that the three perception studies of coherence relied strictly on voice synthesis, we would highlight the possible expansion to the case of real-voice choral signals.

In our review, the two multi-tracking methods of prerecording or live recordings have both advantages and limitations of their own, depending on the research questions. Prerecordings were favoured in studies as in this way it is very easy to isolate the stimulus signal from the experimental recordings of participants. One disadvantage is that it can add variables (such as auditory feedback) that can heavily influence the results. For instance, the self-to-other ratio has been shown to influence intonation and vibrato behaviour.[34] In other words, the monitoring levels of the singers influence the vocal response to the stimuli. This can also depend on whether the stimulus is presented through speakers or headphones (and their quality and frequency response); and in the case of speakers, special attention would have to be given to acoustics as well.

For live multi-tracked recording, studies successfully reported the use of close omnidirectional microphones,[45,59] although a justification for the specific choice of omnidirectional—instead of directional—microphones has not been addressed. One possible reason could be the proximity effect introduced by directional microphones, which in choral singing applications may result in increased low-end spectrum recordings, depending on each particular microphone. (Some manufacturers can often compensate the frequency response for the close proximity applications that the microphones are designed for.)

As additional studies have emphasized the importance of isolated signals,[31,68] and data analyses and mathematical methods strongly rely on signal quality and noise reduction,[64,69] the trade off between (1) a flat response but increased bleed from omnidirectional microphones and (2) a non-ideal frequency response but slightly-increased isolation from directional microphones must be considered. This can depend on the post production treatment of data. For the case of f_o analyses, it would seem plausible that the proximity effect could actually be beneficial as it increases low-frequency response of close sources (usually where the f_o of interest is found), while attenuating the low frequency response of far sources (where the f_o of others may be found) and limiting bleed to higher frequencies, if any. However, for other types of analyses, like looking at ratio of f_o to other frequencies, then proximity effect could be undesirable. Another possible explanation for the use of omnidirectional microphones may as well be plosive or distortion artefacts. But as mentioned, this has not been described in the studies of this review.

In simultaneous singing it is important to obtain isolated signals to study effectively the individual vibratos from multiple singers. However, Duncan[48] successfully extracted frequency information of individual voices from stereo recordings given that the singers were performing a piece in polyphony, with different frequency components that didn't have obstructive harmonics. This is of course restrictive in terms of potential musical material and would not be appropriate for unison voices. The use of multi-tracking techniques and also technologies such as Lx or contact microphones as demonstrated by Jers and Daffern[45,59] specifically aim to support multi-voice signal analysis and remove this limitation, successfully recording polyphonic and unison singing in real time.

Vibrato and Choral Singing

Five categories of aims and objectives were identified through the review. It is interesting to note that some studies reported objectives while others reported aims or research questions. The category addressed by most studies was the theme we called Style, which aimed to study the choral sound of individual singers compared to their solo singing and other genres such as opera or early music. Only one of these included perception analyses, which is surprising considering it could be argued that the essence of this category is a perceptual standpoint: What individual factors contribute to the choral sound?

The category of Style illustrates how different types of choral singing can have different aesthetic ideals—perhaps tied to the music genre or regional context. In the study by Coleman,[43] the author writes: "A Broadway chorus has a different sound quality from an excellent church choir; a barbershop quartet produces sound differently than does a quarter of opera singers." And another study[46] from the same category describes that "choral style favours minimal vibrato, and barbershop style generally forbids vibrato." This latter comparison is entangled with the Intonation category, where in barbershop singing "great care is devoted to intonation"[70] and harmonization to avoid beats and create the *lock and ring* effect. Likewise, the effects of vibrato in the consonance and/or salience of harmonies, especially close harmonies, is a topic that could bring further insights to choral research.

Studies in the Adjustment category demonstrate that singers have the capability to change their vibrato behaviour. The degree to which this is a conscious or unconscious behaviour is still not clear. However, as mentioned above, studies have shown that age, vocal training, singers' experience singing together, or music genre (style) can influence vibrato behaviour. This is another point that emphasizes the continuum between the theme categories that we presented.

Studies that focus on the adaptations of single voices, whilst not conducting an ecological study of choral singing per se, provide foundational evidence around the possibilities of vibrato synchronization in choral singing interaction: If it's possible for one singer to adjust their vibrato in real time to a stimulus, a pair of singers simultaneosly adjusting could behave as a coupled oscillator sensitive to changes in both vibrations. It could be questioned, however, if research could transpose the effects obtained from prerecorded material to those from live group singing setups due to the higher complexity needed to adapt in two-way or multiple-way interactions—"Complexity is not just complicated stuff but a unique quality that emerges from the relationship or interaction among elements."[61] Further research could seek to answer this question by comparing the level of adaptation with a static stimulus versus that with another performer singing in real time.

This is the main essence of the interaction category: The interpersonal relationship of singing voices. This category is specially relevant to the review given that it directly addresses our research question of how voices relate to each other in group singing in terms of vibrato. In this regard, three studies provided compelling evidence of forms of oscillatory synchrony. The common interest of vibrato synchronization between these studies is not surprising given that it could be seen as a proxy for the *sense of ensemble* between performers. Singers being in high synchrony probably suggest they are aware and receptive to each other, which may in turn have positive implications on the output sound. This is, however, still an open question. The studies by Goodwin and Daffern[45,50] hypothesized that vibrato synchrony could improve blend, a perceptual concept and key objective in choral sound. Both production studies provided evidence of vibrato synchronization within singers to that end, although the perceptual significance of this hypothesis is yet to be confirmed through perceptual tests of choral blend.

Excluded records

Some key additional records and their findings are worth mentioning due to their relevance and implications regardless of inclusion status. It was not uncommon for us to find studies providing exceptional insights around vocal vibrato but in a non-choral context; and conversely, studies considering choral singing characteristics but without considering vibrato.

Regarding choral singing, a major body of work that considers the role of vibrato is a series of pedagogical articles by *The Choral Journal*.[22–25] The early article *Factors Related to Choral Blend* describes blend in the choral sound as being an essential achievement that in turn is affected by vocal tone (a psychoacoustic term) and vibrato. In a survey to choral directors about the factors associated with blend, 40% graded vibrato "very important", 38% "important", and 20% "a factor but not of primary importance". This agrees with findings in our review that deal with the choral sound and choral singing modes. Studies analyzing vibrato production showed that singers have different characteristics in choral singing modes and suggest that research could trace effects of vibrato behaviour as a factor also associated with blend.

The more recent study by Hinkley[67] studied the vibrato response to stimuli recorded from a pair of professional choral singers who served as *vocal models*: a baritone with experience in audio engineering and a soprano with experience as choral director. The two vocal models recorded the stimuli with "legato articulation at approximately 60 bpm on the neutral syllable 'tah"' with two vibrato conditions—vibrato and minimal vibrato—and also a set of sung melodies to consider a more choral-voice scenario. The stimuli were presented to 76 high school and undergraduate choral singers in a matching-based experiment, female students responding to the female model, and male students to the male model (a method based on previous studies referenced in Hinkley[67]). This experiment expands on the findings by Dromey[47] in the Adjustment category, which questioned if vibrato adjustments could stand after simulation ceased: In Hinkley's experiment, participants heard the voice model example, then sung themselves right afterwards. Results showed that choral models did have an effect in the vocal vibrato of the students, finding differences in rate and extent.

From the excluded studies, only one was due to the item being unavailable. It corresponds to a reference given in the introductory chapter *Fascinating and Intriguing Vibrato* by Philippe Dejonckere from the book *Vibrato*,[10] which states: "It has been claimed that vocalists singing a duet can synchronize their vibrato rates, but there is no experimental evidence for this.[71]" Although the title and subject seem quite relevant to the review, it is unknown to us if the reference is a full paper in the conference proceedings and presents vibrato outcomes. This reference and the full list of the excluded records is presented in Appendix B, Table B.3.

Future Work

Considering what we learned from the review, vibrato oscillations seem a prominent research avenue in group singing. As the review shows preliminary evidence and measurements on this topic, we note that some of the potential strengthening aspects are the need of more data and extensive/robust analyses; and regarding the experimental methods, further exploration of how to best acquire clean signals in choral context and how to best isolate or control the many variables that take place in group singing to understand the individual relationships of each one. As such, in the next subsections we present a new perspective for data analysis, and an additional experimental method in choral singing research.

Analysis Techniques: Complex Vibrato

In his vibrato review,[7] Sundberg acknowledges that research on the extent and rate of vibrato has been extensive while not much attention has been given to waveform and regularity. This reliance on extent and rate, which in the case of a single note, involving averaging using either the arithmetic or geometrical mean, has proven insightful in terms of understanding the parts that conform vibrato, but also limited in terms of the variability and relationship understanding.

In 1987, Rothman and Arroyo[72] described that "Our ultimate goal in studying vibrato is to understand more fully the three parameters that comprise it [here referring to extent, rate, and amplitude modulation], their interrelationship, and their relationship to perception", and concluded that, "we are immensely engrossed in scientific exploration of large amounts of fascinating, highly variable data." In this vein, studies have successfully utilised the SD. For instance, in their investigations of *good* versus *poor* quality vibrato, Diaz & Rothman in 2003[12] versus measured the extent and rate to calculate the time variability and SD to estimate the vibrato regularity.

As future work, perhaps further insights could be obtained by thinking of vibrato oscillations not from an acoustical but more of a biological perspective, from where it's really derived. Research on biological rhythms has long been baffled by the complexity of "change, flow, and rhythm, mostly in things that are alive."[73] The book *Sync: The Emerging Science of Spontaneous Order*[74] describes how scientists have used modeling of nonlinear differential equations to study rich behaviour and synchronization, where the nonlinear properties of a system denote that the whole is different than the sum of the parts. “In science, we do reductionism”, mentioned the author Strogatz about Sync,[74] “and that has been phenomenally successful for every branch of science. But the great frontier in science today is what happens when you try to go back, to put the parts together to understand the whole. That’s the field of complex systems.” This turns particularly interesting in the context of choral singing.

Studies in the category of interaction between voices report the vibrato contours in the time domain—given that they are correlated in time. An alternative way to observe the evolution of coupled f_o could be found in dynamical systems by observing the qualitative interaction of vibrato in a phase space, illustrating the overall pattern of the f_o oscillations. Dynamics and nonlinearity are by no means novel concepts in voice science, where studies have investigated perturbations *within* the voice,[75−80] but are not yet explored in the context of vibrato and/or group singing.

The coherence or incoherence of coupled vibratos can be studied through the lens of dynamical systems to gain insight about potential adaptative interactions. Differences in phases such as the 180° vibrato stimuli in Erickson[49] or the anti-phase synchronization in Duncan[48] would resemble a periodic limit cycle, recalling that these signals were purely sinusoidal. Far much harder to characterise—if possible—would be the complex interactions that may arise in real voice recordings.

Virtual Choirs

Other avenues of future research into vibrato in group singing could be found from emerging methods for evaluating other methods of choral singing, such as those explored in Daffern et al. 2019 which include the implementation of virtual reality technologies to improve the ecology of the experiments.[81]

Implications of Choral Vibrato Research

This last mentioned study is a continuum to our final perspective which brings us to the fundamental justifications of the review—the experiences of choral singers and the well-being benefits that can accompany choral singing, and how we can further understand them. According to Sundberg, choral singing is “probably the most widespread type of singing”[82] and studies have shown that during performances singers can experience synchronization of cardiac and respiratory patterns.[32] (Also brain rhythms synchronization in the case of duet music improvisation.[83])

Synchronization of bio-measures might support qualitative evidence of well-being increases that have been reported in choral singing,[84] which would agree with a biomathematical perspective that considers the human body as a collection of oscillations—an orchestra of oscillations—that in persistent cases and events tends to intra- or inter-synchronize, be it in phase or out of phase. “For reasons we don’t yet understand, the tendency to synchronize is one of the most pervasive drives in the universe”, describes Strogatz,[74] “and, for some reason, it often gives us pleasure. We like to dance together, sing in a choir, play in a band.”

The limitless scenarios that can arise from vibrato oscillations in the voice might be yet another view from where to study synchronization and well being in choral singing, a view that may in turn spotlight distinct sounds to auditory perception—*the sound of cycles in sync*.[74]

Limitations

A limitation of the current study is the generality of our search and inclusion criteria. As we aimed to provide a wide, comprehensive analysis of the topics involved in vibrato behaviour during choral singing, our findings contain a higher outcome variation than is perhaps usually sought in systematic reviews. Studies providing meta-analyses can resort to techniques to compensate for different methodologies or data estimations from statistics used across studies,[85] but in our case and with our inclusion criteria, outcomes and methods proved to be too sparse, and too little research included, to consider quantitative synthesis. The positive aspect of this is that we have instead provided a perspective of the landscape of research in the area of choral vibrato from which we can consider the most useful paths for future research.

CONCLUSION

In this systematic review, we have shown there are relatively few empirical studies of vibrato production and perception that specifically address vibrato behaviour during group singing tasks, with only 17 papers included in the review. However, this body of work sits within a vast amount of scholarly and performance-based literature around vibrato and choral singing and is highly relevant in complementing and contributing to the broader scope of the work on this topic.

The common approaches that were identified highlight the challenges of data capture and analysis of multi-voice audio signals and highlight the value of the specific approach of simultaneous multi-tracking and/or Lx/EGG capture of vocal fold activity. High variability in methodologies, research questions and limited data-sets reduce the value of any meta-analysis or synergy of findings without future research.

In summary, with the current body of literature, we cannot draw general conclusions from the review, but we have recognized the main subareas and methods which have shown to be fruitful and in which research can continue advancing. The relevance of this work to singing practice is well evidenced in light of its prominence as a vocal feature in choirs and further questions that will collectively shed light on the complex relationships of this oscillatory pattern called vibrato may prove valuable beyond singing practice to understand joint action behaviours and broader concepts of choral blend and singing together.

FUNDING

The review was partly funded by a CONACYT-FINBA research scholarship (N° 795214). Funders had no role in study design, collection, analysis, or publication decisions of the review.

APPENDIX A. PUBMED FULL SEARCH EXAMPLE

1. "vibrato"[All Fields] OR "vibratos"[All Fields] OR "pitch variation"[All Fields] OR "fundamental frequency variation"[All Fields]
2. "singing"[MeSH Terms] OR "singing"[All Fields] OR "sing"[All Fields] OR ("voice" [MeSH Terms] OR "voice" [All Fields] OR "voices"[All Fields] OR "voice s"[All Fields] OR "voiced"[All Fields] OR "voicing"[All Fields]) OR ("vocal"[All Fields] OR "vocales"[All Fields] OR "vocalic"[All Fields] OR "vocalisation"[All Fields] OR "vocalisations"[All Fields] OR "vocalised"[All Fields] OR "vocalising"[All Fields] OR "vocalization"[All Fields] OR "vocalizations"[All Fields] OR "vocalize"[All Fiel ds] OR "vocalized"[All Fields] OR "vocalizer"[All Fields] OR "vocalizers"[All Fields] OR "vocalizes"[All Fields] OR "vocalizing"[All Fields] OR "vocally"[All Fields] OR "vocals"[All Fields]) OR ("phonate"[All Fields] OR "phonated"[All Fields] OR "phonating"[All Fields] OR "phonation"[MeSH Terms] OR "phonation"[All Fields] OR "phonations"[All Fields] OR "phonational"[All Fields])
3. "choral"[All Fields] OR "chorus"[All Fields] OR ("choir" [All Fields] OR "choirs" [All Fields]) OR "unison"[All Fields] OR "duet"[All Fields] OR "trio"[All Fields] OR ("quartet"[All Fields] OR "quartets"[All Fields]) OR ("quintet"[All Fields] OR "quintets"[All Fields]) OR "group singing"[All Fields] OR "ensemble singing"[All Fields]
4. 1 AND 2 AND 3

Translations.

- vibrato: "vibrato"[All Fields] OR "vibratos"[All Fields]
- sing: "singing"[MeSH Terms] OR "singing"[All Fields] OR "sing"[All Fields]
- voice: "voice"[MeSH Terms] OR "voice"[All Fields] OR "voices"[All Fields] OR "voice's"[All Fields] OR "voiced"[All Fields] OR "voicing"[All Fields]
- vocal: "vocal"[All Fields] OR "vocales"[All Fields] OR "vocalic"[All Fields] OR "vocalisation"[All Fields] OR "vocalisations"[All Fields] OR "vocalised"[All Fields] OR "vocalising"[All Fields] OR "vocalization"[All Fields] OR "vocalizations"[All Fields] OR "vocalize"[All Fields] OR "vocalized"[All Fields] OR "vocalizer"[All Fields] OR "vocalizer's"[All Fields] OR "vocalizers"[All Fields] OR "vocalizes"[All Fields] OR "vocalizing"[All Fields] OR "vocally"[All Fields] OR "vocals"[All Fields]
- phonation: "phonate"[All Fields] OR "phonated"[All Fields] OR "phonating"[All Fields] OR "phonation"[MeSH Terms] OR "phonation"[All Fields] OR "phonations"[All Fields] OR "phonational"[All Fields]
- choir: "choir"[All Fields] OR "choirs"[All Fields]
- quartet: "quartet"[All Fields] OR "quartets"[All Fields]
- quintet: "quintet"[All Fields] OR "quintets"[All Fields]

APPENDIX B. FULL DATA

This appendix shows the records and data for the review in Tables B.1, B.2, and B.3.

TABLE B.1.
Methodology Approaches of Studies Included in the Review

Study	Synthesis	Multi-track		Stereo/Binaural	Lx/Contact
		Prerecording	Live		
Coleman 1994				×	×
Culling & Summerfield 1995	×				
Daffern 2017			×		×
Dai & Dixon 2019		×			
Dromey et al. 2003					
Duncan et al. 2000				×	
Erickson et al. 2012					
Goodwin 1980		×			
Jers & Ternström 2004			×		
Le Beux et al. 2011	×				
Mann 2014				×	
McAdams 1989	×				
Reid et al. 2007		×			
Rossing et al. 1987		×		×	
Sacerdote 1957				×	
Ternström et al. 1988	×				
Ternström & Sundberg 1988	×	×		×	×
Total	**6**	**6**	**2**	**6**	**3**

TABLE B.2.
Objective Category of Each Study

Study	Adjustment	Identification	Interaction	Intonation	Style
Coleman 1994					×
Culling & Summerfield 1995		×			
Daffern 2017			×		
Dai & Dixon 2019				×	
Dromey et al. 2003	×				
Duncan et al. 2000			×		
Erickson et al. 2012		×			
Goodwin 1980					×
Jers & Ternström 2004			×		
Le Beux et al. 2011				×	
Mann 2014					×
McAdams 1989		×			
Reid et al. 2007					×
Rossing et al. 1987					×
Sacerdote 1957					×
Ternström et al. 1988					×
Ternström & Sundberg 1988				×	
Total	**1**	**3**	**3**	**3**	**7**

TABLE B.3.
List of Assessed Records and Exclusion Criteria

Study	No Vibrato	No Choral Singing	No Scientific Paper	Other
Electronic databases				
Berghs et al. 2013[66]		×		
Reddy & Subramanian 2015[19]		×		
Howard 2018[86]		×		
Takasu 1997[87]		×		
Marchini 2014[88]	×	×		
Wooding & Nix 2016[89]		×		
Dai & Dixon 2019[90]	×			
Nix 2015[20]		×		
Maher & Beauchamp 1994[91]	×	×		
Key journals				
Ravi et al. 2019[92]	×			
Kirsh et al. 2013[93]	×			
Howard et al.[65]	×			
Nix et al. 2016[94]		×		
Duvvuru & Erickson 2016[95]		×		
Guzman et al. 2012[14]		×		
Ternström 1991[34]			×	
D'Amario et al. 2020[68]	×			
Sacerdote 1956[96]			×	
Brown 1993[35]			×	
Dai & Dixon 2019[97]	×			
Grell et al. 2009[98]	×			
Mauch et al. 2014[52]	×			
Other sources				
Sublett 2019[99]			×	
Olson 2008[100]			×	
Nix 2014[21]			×	
Galante 2011[24]			×	
Półrolniczak & Kramarczyk 2013[37]		×		
Wyatt 1967[22]			×	
Sundberg 1988[101]			×	
Katok 2021[25]			×	
Titze et al. 1994[102]		×		
Titze et al. 2002[15]		×		
Carter et al. 2010[103]			×	
Culling & Darwin 1993[104]	×	×		
Dejonckere et al. 1990[71]				×
Reference lists				
Sundberg & Lindqvist 1973[105]	×	×		
Rossing et al. 1986[64]	×			
Howard 2007[63]	×			
Howard et al. 2013[36]		×		
Troup 1981[106]	×	×		
King & Horii 1993[107]				
Culling & Darwin 1993[108]	×			
Demany & Semal 1990[109]		×		
Marin & McAdams 1996[110]		×		
McCoy 2011[26]			×	
Ekholm 2000[111]	×			
Ford 2003[112]	×			
Howard et al. 2012[113]		×		
Daugherty 1999[114]	×			
Daugherty 2003[115]	×			
Daugherty et al. 2013[116]	×			
Hsiao et al. 1994[117]		×		

(*Continued*)

TABLE B.3. (*Continued*)

Study	No Vibrato	No Choral Singing	No Scientific Paper	Other
Sundberg et al. 1998[118]		×		
Rasch 1978[119]		×		
Gardner et al. 1989[120]		×		
Carlyon 1991[121]		×		
Carlyon 1992[122]		×		
Carlyon 1994[123]		×		
Darwin & Culling 1990[124]			×	
Darwin 1981[125]	×			
Chalikia & Bregman 1989[126]	×			
Chalikia & Bregman 1993[127]	×			
Wilson et al. 1990[128]		×		
Cohen & Chen 1992[129]	×	×		
Darwin et al. 1994[130]		×		
Moore et al. 1985[131]	×	×		
Zwicker 1984[132]	×	×		
Assmann & Summerfield 1990[133]	×	×		
Gardner & Darwin 1986[134]		×		
Total	**28**	**35**	**15**	**1**

REFERENCES

1. Potter J. *Vocal authority: Singing style and ideology*. Cambridge University Press; 2006.
2. Butte CJ, Zhang Y, Song H, Jiang JJ. Perturbation and nonlinear dynamic analysis of different singing styles. *Journal of Voice*. 2009;23(6):647–652.
3. Neubauer J, Edgerton M, Herzel H. Nonlinear phenomena in contemporary vocal music. *Journal of Voice*. 2004;18(1):1–12.
4. Scherer KR, Sundberg J, Fantini B, Trznadel S, Eyben F. The expression of emotion in the singing voice: Acoustic patterns in vocal performance. *The Journal of the Acoustical Society of America*. 2017;142(4):1805–1815.
5. Seashore CE. The natural history of the vibrato. In: *Proceedings of the National Academy of Sciences of the United States of America*. volume 17. National Academy of Sciences; 1931:623–626.
6. Studies in the psychology of music. The vibrato. In: Seashore CE, ed. volume 1, University of Iowa; 1932.
7. Sundberg J. Acoustic and psychoacoustic aspects of vocal vibrato. *STL-QPSR*. 1994;35:45–68.
8. Daffern H, Howard DM. Voice source comparison between modern singers of early music and opera. *Logopedics Phoniatrics Vocology*. 2010;35(2):68–73.
9. Dromey C, Reese L, Hopkin JA. Laryngeal-level amplitude modulation in vibrato. *Journal of Voice*. 2009;23(2):156–163.
10. Dejonckere PH, Hirano M, Sundberg J. *Vibrato*. Singular Publishing Group; 1995.
11. Sundberg J. Perceptual aspects of singing. *Journal of Voice*. 1994;8(2):106–122.
12. Diaz JA, Rothman HB. Acoustical comparison between samples of good and poor vibrato in singers. *Journal of Voice*. 2003;17(2):179–184.
13. Anand S, Wingate JM, Smith B, Shrivastav R. Acoustic parameters critical for an appropriate vibrato. *Journal of Voice*. 2012;26(6):820e19–820e25.
14. Guzman MA, Dowdall J, Rubin AD, et al. Influence of emotional expression, loudness, and gender on the acoustic parameters of vibrato in classical singers. *Journal of Voice*. 2012;26(5):675e5–675e11.
15. Titze IR, Story B, Smith M, Long R. A reflex resonance model of vocal vibrato. *The Journal of the Acoustical Society of America*. 2002;111(5):2272–2282.
16. Horii Y. Acoustic analysis of vocal vibrato: A theoretical interpretation of data. *Journal of Voice*. 1989;3(1):36–43.
17. Meron Y, Hirose K. Synthesis of vibrato singing. *2000 IEEE International Conference on Acoustics, Speech, and Signal Processing*. volume 2. IEEE; 2000:745–748.
18. Amir N, Michaeli O, Amir O. Acoustic and perceptual assessment of vibrato quality of singing students. *Biomedical Signal Processing and Control*. 2006;1(2):144–150.
19. Reddy AA, Subramanian U. Singers' and nonsingers' perception of vocal vibrato. *Journal of Voice*. 2015;29(5):603–610.
20. Nix J. Listener preferences for vibrato rate and extent in synthesized vocal samples. In: *Proceedings of Meetings on Acoustics*. volume 23. Acoustical Society of America; 2015:035002.
21. Nix J. Shaken, not stirred: Practical ideas for addressing vibrato and nonvibrato singing in the studio and the choral rehearsal. *Journal of Singing*. 2014;70(4):411–418.
22. Wyatt L. Factors related to choral blend: Tone quality, vibrato, intonation. *The Choral Journal*. 1967;8(2):7–9.
23. Walker G. Good vibrations: Vibrato, science, and the choral singer. *The Choral Journal*. 2006;47(6):36–46.
24. Galante B. Vibrato and choral acoustics: Common voice science issues for the choral conductor. *The Choral Journal*. 2011;51(7):67–78.
25. Katok D. Healthy minimization of vibrato: An exploration of straight tone. *The Choral Journal*. 2021;62(4):8–19.
26. McCoy S. The choir issue, part 1. *Journal of Singing*. 2011;67(3):297–301.
27. Ternström S. Choir acoustics - an overview of scientific research published to date. *TMH-QPSR*. 2002;43(1):1–8.
28. D'Amario S, Daffern H, Bailes F. A new method of onset and offset detection in ensemble singing. *Logopedics Phoniatrics Vocology*. 2019;44(4):143–158.
29. Seibert C. *Using performance sociograms to investigate inter-performer relationships in music ensembles*. Oxford University Press; 2021:155–161.

30. Kearney G, Daffern H, Thresh L, et al. Design of an interactive virtual reality system for ensemble singing. *Interactive Audio Systems Symposium*2016.York, UK
31. Daffern H, D'Amario S. *Understanding expressive ensemble singing through acoustics*. Oxford University Press; 2021:129–138.
32. Müller V, Lindenberger U. Cardiac and respiratory patterns synchronize between persons during choir singing. *PloS ONE*. 2011;6(9): e24893.
33. Jers H, Ternström S. Intonation analysis of a multi-channel choir recording. *TMH-QPSR*. 2005;47(1):1–6.
34. Ternström S. Physical and acoustic factors that interact with the singer to produce the choral sound. *Journal of Voice*. 1991;5(2):128–143.
35. Brown LR. Effects of vibrato and vowel matching on choral blend: A correlation of spectral analyses and perceptual evaluations. *126th Meeting*. volume 94. Acoustical Society of America; 1993:1860.
36. Howard DM, Daffern H, Brereton J. Four-part choral synthesis system for investigating intonation in a cappella choral singing. *Logopedics Phoniatrics Vocology*. 2013;38(3):135–142.
37. Półrolniczak E, Kramarczyk M. Analysis of the signal of singing using the vibrato parameter in the context of choir singers. *Journal of Electronic Science and Technology*. 2013;11(4):417–423.
38. Liberati A, Altman DG, Tetzlaff J, et al. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: Explanation and elaboration. *Journal of Clinical Epidemiology*. 2009;62(10):e1–e34.
39. Moher D, Liberati A, Tetzlaff J, Altman DG, Group P. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLoS Medicine*. 2009;6(7):e1000097.
40. Akers J, Aguiar-Ibáñez R, Sari AB, Beynon S, Booth A, et al. *Systematic reviews: CRD's guidance for undertaking reviews in health care*. 3 Centre for Reviews & Dissemination, University of York; 2008.
41. Sampson M, McGowan J, Cogo E, et al. An evidence-based practice guideline for the peer review of electronic search strategies. *Journal of Clinical Epidemiology*. 2009;62(9):944–952.
42. McGowan J, Sampson M, Salzwedel DM, et al. PRESS peer review of electronic search strategies: 2015 guideline statement. *Journal of Clinical Epidemiology*. 2016;75:40–46.
43. Coleman RF. Acoustic and physiologic factors in duet singing: A pilot study. *Journal of Voice*. 1994;8(3):202–206.
44. Culling JF, Summerfield Q. The role of frequency modulation in the perceptual segregation of concurrent vowels. *The Journal of the Acoustical Society of America*. 1995;98(2):837–846.
45. Daffern H. Blend in singing ensemble performance: Vibrato production in a vocal quartet. *Journal of Voice*. 2017;31(3):385e23–385e29.
46. Dai J, Dixon S. Intonation trajectories within tones in unaccompanied soprano, alto, tenor, bass quartet singing. *The Journal of the Acoustical Society of America*. 2019;146(2):1005–1014.
47. Dromey C, Carter N, Hopkin A. Vibrato rate adjustment. *Journal of Voice*. 2003;17(2):168–178.
48. Duncan M, Williams C, Troup G. Vibrato frequency and phase lock in operatic duet quality. *Acoustics Australia*. 2000;28(1):5–9.
49. Erickson ML, Gaskill CS. Can listeners hear how many singers are singing? The effect of listener's experience, vibrato, onset, and formant frequency on the perception of number of simultaneous singers. *Journal of Voice*. 2012;26(6):817e1–817e13.
50. Goodwin AW. An acoustical study of individual voices in choral blend. *Journal of Research in Music Education*. 1980;28(2):119–128.
51. Le Beux S, Feugère L, d'Alessandro C. Chorus digitalis: Experiment in chironomic choir singing. *Annual Conference of the International Speech Communication Association*. ISCA; 2011:2005–2008.Firenze, Italy
52. Mann LM. Effects of solo and choral singing modes on vibrato rate, extent, and duration exhibited by undergraduate female singers. *International Journal of Research in Choral Singing*. 2014;5(1):26–38.
53. McAdams S. Segregation of concurrent sounds. I: Effects of frequency modulation coherence. *The Journal of the Acoustical Society of America*. 1989;86(6):2148–2159.
54. Reid KL, Davis P, Oates J, Cabrera D, Ternström S, Black M, Chapman J. The acoustic characteristics of professional opera singers performing in chorus versus solo mode. *Journal of Voice*. 2007;21(1):35–45.
55. Rossing TD, Sundberg J, Ternström S. Acoustic comparison of soprano solo and choir singing. *The Journal of the Acoustical Society of America*. 1987;82(3):830–836.
56. Sacerdote GG. Researches on the singing voice. *Acustica*. 1957;7(2):61–68.
57. Ternström S, Friberg A, Sundberg J. Synthesizing choir singing. *Journal of Voice*. 1988;1(4):332–335.
58. Ternström S, Sundberg J. Intonation precision of choir singers. *The Journal of the Acoustical Society of America*. 1988;84(1):59–69.
59. Jers H, Ternström S. Intonation analysis of a multi-channel choir recording. *Baltic-Nordic Acoustics Meeting*2004.Mariehamn, Åland, Finland
60. D'Amario S, Daffern H. Using electrolaryngography and electroglottography to assess the singing voice: A systematic review. *Psychomusicology: Music, Mind, and Brain*. 2017;27(4):229–243.
61. Buzsáki G. *Rhythms of the brain*. Oxford University Press; 2006.
62. Mauch M, Frieler K, Dixon S. Intonation in unaccompanied singing: Accuracy, drift, and a model of reference pitch memory. *The Journal of the Acoustical Society of America*. 2014;136(1):401–411.
63. Howard DM. Intonation drift in a capella soprano, alto, tenor, bass quartet singing with key modulation. *Journal of Voice*. 2007;21(3):300–315.
64. Rossing TD, Sundberg J, Ternström S. Acoustic comparison of voice use in solo and choir singing. *The Journal of the Acoustical Society of America*. 1986;79(6):1975–1981.
65. Howard DM, Welch GF, Himonides E, Owens M. The developing female chorister voice: Case-study evidence of musical development. *Journal of Voice*. 2019;33(4):516–525.
66. Berghs G, Creylman N, Avaux M, Decoster W, de Jong F. A lifetime of professional singing: Voice parameters and age in the Netherlands Radio Choir. *Logopedics Phoniatrics Vocology*. 2013;38(2):59–63.
67. Hinkley SP. Effects of vibrato and pitch-varied vocal models on acoustic measures of high school and undergraduate singers' vocal performance. *International Journal of Research in Choral Singing*. 2021;9:1–21.
68. D'Amario S, Howard DM, Daffern H, Pennill N. A longitudinal study of intonation in an a cappella singing quintet. *Journal of Voice*. 2020;34(1):159e13–159e27.
69. Brain-computer interfaces: Principles and practice. In: Wolpaw JR, Wolpaw EW, eds. Oxford University Press; 2012.New York, NY
70. Hagerman B, Sundberg J. Fundamental frequency adjustment in barbershop singing. *STL-QPSR*. 1980;21(1):028–042.
71. Dejonckere PH, Miller R, Wieneke G. Vibrato in duet singers. In: *Proceedings CoMeT Congress*1990.Cairo
72. Rothman HB, Arroyo AA. Acoustic variability in vibrato and its perceptual significance. *Journal of Voice*. 1987;1(2):123–141.
73. Winfree AT. *The geometry of biological time*. 2 Springer; 2000.
74. Strogatz SH. *Sync: The emerging science of spontaneous order*. Hyperion; 2003.
75. Herzel H, Berry D, Titze I, Steinecke I. Nonlinear dynamics of the voice: Signal analysis and biomechanical modeling. *Chaos*. 1995;5(1):30–34.
76. Matassini L, Hegger R, Kantz H, Manfredi C. Analysis of vocal disorders in a feature space. *Medical Engineering & Physics*. 2000;22(6):413–418.
77. Herzel H. Bifurcations and chaos in voice signals. *Applied Mechanics Reviews*. 1993;46(7):399–413.
78. Anikin A. The perceptual effects of manipulating nonlinear phenomena in synthetic nonverbal vocalizations. *Bioacoustics*. 2020;29(2):226–247.
79. Little M, Mcsharry P, Roberts S, Costello D, Moroz I. Exploiting nonlinear recurrence and fractal scaling properties for voice disorder detection. *Nature Precedings*. 2007:1–35.

80. Švec JG, Schutte HK, Miller DG. A subharmonic vibratory pattern in normal vocal folds. *Journal of Speech, Language, and Hearing Research*. 1996;39(1):135–143.
81. Daffern H, Camlin D, Egermann H, et al. Exploring the potential of virtual reality technology to investigate the health and well being benefits of group singing. *International Journal of Performance Arts and Digital Media*. 2019;15(1):1–22.
82. Sundberg J. *The science of the singing voice*. Northern Illinois University Press; 1987.
83. Müller V, Saenger J, Lindenberger U. Intra and inter-brain synchronization during musical improvisation on the guitar. *PLoS ONE*. 2013;8(9):e73852.
84. Camlin DA, Daffern H, Zeserson K. Group singing as a resource for the development of a healthy public: A study of adult group singing. *Humanities and Social Sciences Communications*. 2020;7(1):1–15.
85. Luo D, Wan X, Liu J, Tong T. Optimally estimating the sample mean from the sample size, median, mid-range, and/or mid-quartile range. *Statistical Methods in Medical Research*. 2018;27(6):1785–1805.
86. Howard DM. The vocal tract organ: A new musical instrument using 3-D printed vocal tracts. *Journal of Voice*. 2018;32(6):660–667.
87. Takasu M. Vocalness of the female singing voice. *Journal of the Acoustical Society of Japan*. 1997;18(1):19–28.
88. Marchini M, Ramirez R, Papiotis P, Maestre E. The sense of ensemble: A machine learning approach to expressive performance modelling in string quartets. *Journal of New Music Research*. 2014;43(3):303–317.
89. Wooding R, Nix J. Perception of non-vibrato sung tones: A pilot study. *Journal of Voice*. 2016;30(6):762e15–762e21.
90. Dai J, Dixon S. Understanding intonation trajectories and patterns of vocal notes. *International Conference on Multimedia Modeling*. Springer; 2019:243–253.
91. Maher RC, Beauchamp JW. Fundamental frequency estimation of musical signals using a two-way mismatch procedure. *The Journal of the Acoustical Society of America*. 1994;95(4):2254–2263.
92. Ravi SK, Shabnam S, George KS, Saraswathi T. Acoustic and aerodynamic characteristics of choral singers. *Journal of Voice*. 2019;33(5):803e1–803e5.
93. Kirsh ER, van Leer E, Phero HJ, Xie C, Khosla S. Factors associated with singers' perceptions of choral singing well-being. *Journal of Voice*. 2013;27(6):786e25–786e32.
94. Nix J, Perna N, James K, Allen S. Vibrato rate and extent in college music majors: A multicenter study. *Journal of Voice*. 2016;30(6):756e31–756e41.
95. Duvvuru S, Erickson M. The effect of timbre, pitch, and vibrato on vocal pitch-matching accuracy. *Journal of Voice*. 2016;30(3):378e1–378e12.
96. Sacerdote GG. Researches on the singing voice. *51th Meeting*. volume 28. Acoustical Society of America; 1956:789–790.
97. Dai J, Dixon S. Singing together: Pitch accuracy and interaction in unaccompanied unison and duet singing. *The Journal of the Acoustical Society of America*. 2019;145(2):663–675.
98. Grell A, Sundberg J, Ternström S, Ptok M, Altenmüller E. Rapid pitch correction in choir singers. *The Journal of the Acoustical Society of America*. 2009;126(1):407–413.
99. Sublett V. Vibrato or nonvibrato in solo and choral singing: Is there room for both? *Journal of Singing*. 2009;65(5):539–544.
100. Olson M. Vibrato vs. nonvibrato: The solo singer in the collegiate choral ensemble. *Journal of Singing*. 2008;64(5):561–564.
101. Sundberg J. Synthesizing singing. *115th Meeting*. volume 83. Acoustical Society of America; 1988:S30–S31.
102. Titze IR, Solomon NP, Luschei ES, Hirano M. Interference between normal vibrato and artificial stimulation of laryngeal muscles at near-vibrato rates. *Journal of Voice*. 1994;8(3):215–223.
103. Carter N, Hopkin JA, Dromey C. Volitional control of vibrato in trained singers. *Journal of Singing*. 2010;67(1):9–17.
104. Culling JF, Darwin C. Perceptual separation of simultaneous vowels: Within and across-formant grouping by F0. *The Journal of the Acoustical Society of America*. 1993;93(6):3454–3467.
105. Sundberg J, Lindqvist J. Musical octaves and pitch. *The Journal of the Acoustical Society of America*. 1973;54(4):922–929.
106. Troup GJ. The physics of the singing voice: Measurements on the voices and vocal apparatus of trained singers, and their interpretation. *Physics Reports*. 1981;74(5):379–401.
107. King JB, Horii Y. Vocal matching of frequency modulation in synthesized vowels. *Journal of Voice*. 1993;7(2):151–159.
108. Culling JF, Darwin C. The role of timbre in the segregation of simultaneous voices with intersecting F0 contours. *Perception & Psychophysics*. 1993;54(3):303–309.
109. Demany L, Semal C. The effect of vibrato on the recognition of masked vowels. *Perception & Psychophysics*. 1990;48(5):436–444.
110. Marin CM, McAdams S. The role of auditory beats induced by frequency modulation and polyperiodicity in the perception of spectrally embedded complex target sounds. *The Journal of the Acoustical Society of America*. 1996;100(3):1736–1753.
111. Ekholm E. The effect of singing mode and seating arrangement on choral blend and overall choral sound. *Journal of Research in Music Education*. 2000;48(2):123–135.
112. Ford JK. Preferences for strong or weak singer's formant resonance in choral tone quality. *International Journal of Research in Choral Singing*. 2003;1(1):29–47.
113. Howard DM, Daffern H, Brereton J. Quantitative voice quality analyses of a soprano singing early music in three different performance styles. *Biomedical Signal Processing and Control*. 2012;7:58–64.
114. Daugherty JF. Spacing, formation, and choral sound: Preferences and perceptions of auditors and choristers. *Journal of Research in Music Education*. 1999;47(3):224–238.
115. Daugherty JF. Choir spacing and formation: Choral sound preferences in random, synergistic, and gender-specific chamber choir placements. *International Journal of Research in Choral Singing*. 2003;1(1):48–59.
116. Daugherty JF, Manternach JN, Brunkan MC. Acoustic and perceptual measures of SATB choir performances on two types of portable choral riser units in three singer-spacing conditions. *International Journal of Music Education*. 2013;31(3):359–375.
117. Hsiao TY, Solomon NP, Luschei ES, Titze IR. Modulation of fundamental frequency by laryngeal muscles during vibrato. *Journal of Voice*. 1994;8(3):224–229.
118. Sundberg J, Thörnvik MN, Söderström AM. Age and voice quality in professional singers. *Logopedics Phoniatrics Vocology*. 1998;23(4):169–176.
119. Rasch RA. The perception of simultaneous notes such as in polyphonic music. *Acustica*. 1978;40(1):21–33.
120. Gardner RB, Gaskill SA, Darwin C. Perceptual grouping of formants with static and dynamic differences in fundamental frequency. *The Journal of the Acoustical Society of America*. 1989;85(3):1329–1337.
121. Carlyon RP. Discriminating between coherent and incoherent frequency modulation of complex tones. *The Journal of the Acoustical Society of America*. 1991;89(1):329–340.
122. Carlyon RP. The psychophysics of concurrent sound segregation. *Philosophical Transactions of the Royal Society of London*. 1992;336(1278):347–355.
123. Carlyon RP. Further evidence against an across-frequency mechanism specific to the detection of frequency modulation incoherence between resolved frequency components. *The Journal of the Acoustical Society of America*. 1994;95(2):949–961.
124. Darwin C, Culling JF. Speech perception seen through the ear. *Speech Communication*. 1990;9:469–475.
125. Darwin CJ. Perceptual grouping of speech components differing in fundamental frequency and onset-time. *The Quarterly Journal of Experimental Psychology*. 1981;33(2):185–207.
126. Chalikia MH, Bregman AS. The perceptual segregation of simultaneous auditory signals: Pulse train segregation and vowel segregation. *Perception & Psychophysics*. 1989;46(5):487–496.
127. Chalikia MH, Bregman AS. The perceptual segregation of simultaneous vowels with harmonic, shifted, or random components. *Perception & Psychophysics*. 1993;53(2):125–133.

128. Wilson AS, Hall JW, Grose JH. Detection of frequency modulation in the presence of a second FM tone. *The Journal of the Acoustical Society of America*. 1990;88(3):1333–1338.
129. Cohen MF, Chen X. Dynamic frequency change among stimulus components: Effects of coherence on detectability. *The Journal of the Acoustical Society of America*. 1992;92(2):766–772.
130. Darwin C, Ciocca V, Sandell G. Effects of frequency and amplitude modulation on the pitch of a complex tone with a mistuned harmonic. *The Journal of the Acoustical Society of America*. 1994;95(5):2631–2636.
131. Moore BC, Glasberg BR, Peters RW. Relative dominance of individual partials in determining the pitch of complex tones. *The Journal of the Acoustical Society of America*. 1985;77(5):1853–1860.
132. Zwicker UT. Auditory recognition of diotic and dichotic vowel pairs. *Speech Communication*. 1984;3(4):265–277.
133. Assmann PF, Summerfield Q. Modeling the perception of concurrent vowels: Vowels with different fundamental frequencies. *The Journal of the Acoustical Society of America*. 1990;88(2):680–697.
134. Gardner RB, Darwin C. Grouping of vowel harmonics by frequency modulation: Absence of effects on phonemic categorization. *Perception & Psychophysics*. 1986;40(3):183–187.