informa
healthcare

ORIGINAL ARTICLE

Criteria and tools for objectively analysing the vocal accuracy of a popular song

PAULINE LARROUY-MAESTRI & DOMINIQUE MORSOMME

Logopédie de la Voix, Department of Psychology: Cognition and Behaviour, University of Liège, Belgium

Abstract
This study aims to validate our method for measuring accuracy in a melodic context. We analysed the popular song 'Happy Birthday' sung by 63 occasional and 14 professional singers thanks to AudioSculpt and OpenMusic (IRCAM, Paris, France). In terms of evaluation of the pitch interval deviation, we replicated the profile of occasional singers described in the literature (the slower the performance, the more accurate it is). Our results also confirm that the professional singers sing more accurately than occasional singers but not when a Western operatic singing technique is involved. These results support the relevance of our method for analysing vocal accuracy of occasional and professional singers and led us to discuss adaptations to be implemented for analysing the accuracy of operatic voices.

Key words: *Accuracy, acoustic analysis, popular song, singer, singing voice*

Introduction

The singing voice is an instrument which everyone possesses and can develop (1). Judgement of the quality of sung vocal performance is based on aesthetical criteria related to a specific culture. A survey of 1009 singing teachers from the National Association of Teachers of Singing (NATS) demonstrated that intonation is a criterion of paramount importance, like the tone quality and musicality, in defining vocal quality (2). The definition of accuracy varies depending on the author, but its measurement is always based on variations in fundamental frequency (3).

This parameter is regularly observed in estimating the prevalence of accuracy problems called 'poor-pitch singing' (4), detecting amusia (5), categorizing singers as 'good' or 'bad' (6–9), and investigating the causes of accuracy troubles (for review, see (10)).

Different tasks can be proposed to observe the vocal accuracy. Some involve reproducing sounds (isolated or in short tunes): single pitch-matching (11,12), imitation of single pitches (8,13) or intervals (8), imitation of short pitch patterns (13), of short novel melodies (8), or unfamiliar pitch sequences

(9). Others consist in imitation (6,14) or singing from memory familiar melodies (6,7,9,14).

In a melodic context, acoustical analysis consists first in the segmentation of the auditory signal and the fundamental frequency (F0) estimation. Praat software (15,16) is commonly used (e.g. (7,9)) for the visual inspection of the waveform and the identification of the steady-state phase of each sung note. In these studies, the mean F0 was then estimated and the pitch detection errors (e.g. octave jumps) were manually corrected. Then, the F0 of each note produced can be compared with the target but also between the notes of the performance itself. Several errors can thus be observed (Figure 1): errors in the melodic contour (the produced interval direction deviated from the musical notation, e.g. the second note of the interval is higher instead of lower than the first), pitch interval errors (the direction of the interval is respected, but the distance between the notes is altered), and tonal centre errors (change in tonality during a melodic phrase).

In order to validate our criteria and tools for analysing vocal accuracy, we wished to reproduce an experiment conducted on a general population but

Correspondence: Pauline Larrouy-Maestri, Logopédie de la voix, Département de Psychologie: cognition et comportement, Université de Liège, B-38, Rue de l'Aunaie, 30, 4000 Liège, Belgium. E-mail: pauline.larrouy@ulg.ac.be

RIGHTSLINK()

Accurate version

Contour error at note 2 (this note goes up instead of going down)

Interval error of 200 cents (one tone) between notes 1-2 and 2-3
(the contour of the melody is respected but the interval is too big)

Tonal deviation at note 5 (interval error between notes 4-5 involving
a modulation of the following of the tune)

Figure 1. Illustration of errors observed in a melodic context.

also to verify the effect of vocal expertise on the accuracy of a popular tune.

The accuracy of singing by occasional singers was analysed by Dalla Bella et al. (7). These authors recruited 62 occasional singers to sing the popular song 'Gens du Pays', a song sung to celebrate birthdays in Quebec. They measured the pitch of the 32 notes in this song. Their results indicate that the majority of the population can sing relatively accurately. They also investigated the impact of tempo on the quality of the singing and concluded that, by slowing down the tempo, the accuracy of the singing was closer to that of the professionals. We aimed to reproduce the observations of Dalla Bella et al. (7) about the link between tempo and accuracy, using our criteria and tools for analysis in order to validate them.

Professional singers have the same vocal organs as occasional singers. However, musical training enables the development of general musical expertise as well as expertise specific to the instrument used (17). In the case of the singers, their daily practice has an effect on the voice, in terms of perception (18) and production (7,11,19,20), with the accuracy of intonation significantly increasing thanks to musical training. The singers also acquire knowledge concerning the suitable conditions required for good singing, such as the adoption of appropriate posture (21) or the performance of a vocal warm-up (22).

By comparing the singing of a population of occasional singers who have not received any musical

training with that of professional singers well-versed in singing techniques, we aimed to confirm the effect of vocal expertise on vocal accuracy and thus support the choice of our criteria and tools of analysis for observing it.

In the modern sense of the word, operatic singing designates the technique widely employed in opera and (by extension) more generally in Western classical music (e.g. lieder, cantatas, oratorios, etc.). The acoustic qualities of professional singers are documented by various studies (for reviews, see (23,24)), in a soloist or choir context (25). The intensity of the singer's formant, the presence of vibrato, the maximum phonational frequency range, and the intensity increase with musical experience (e.g. (26–28)). Few studies have examined accuracy in professional singers. Vurma and Ross (29) remarked that when professional singers have to produce intervals, they may be false by 20 to 25 cents, but the singing is still considered as accurate by expert judges. In this study, the focus was on producing isolated intervals, but vocal accuracy in a melodic context was not investigated. The precision of intonation remains necessary in a melodic context in order to satisfy the expectations of our Western culture, to respect musical composition, and to sing with accompanying instruments or in a vocal ensemble. Analysis of vocal performance with an operatic technique, used by classically trained singers, allows us to put to the test the criteria and tools developed for the voices of occasional singers.

Furthermore, through vocal training, professional singers are led to alter their singing in accordance with specified instructions. Even if the vocal technique developed by a singer cannot be taken from him or her, nonetheless we can observe different types of singing depending on the type of musical genre requested. Comparison between the performances of professional singers using an operatic vocal technique or not will enable highlighting of any possible acoustic characteristics to be taken into account for the study of accuracy when an operatic technique is used.

Method

Participants

We analysed the singing of a control group made up of 63 female Occasional Singers (OS) and an experimental group of 14 female operatic singers.

The voices of the OS come from the database 'oai:sldr.org:sldr000774' (available at: http://sldr.org/sldr000774/en). These 63 women were aged from 15 to 75 years old (M = 29.83, SE = 1.89). These subjects were chosen according to musical training criteria: they had received no formal musical training, had never played an instrument, and had never had extra-curricular school lessons in music. For this study, only the performances sung with the correct melodic contour and the correct number of notes (i.e. 21 notes) were selected.

The experienced singers were recruited from the Royal Northern College of Music in Manchester. These 14 women were aged from 19 to 54 years old (M = 24.29, SE = 2.35). They started training in singing from the age of 8 to 17 years old (M = 13, SE = 0.85). The number of years of practice was between 5 and 20 years (M = 9.57, SE = 1.01).

Material

The OS spontaneously sang the French version of the popular tune 'Happy Birthday', which has the same melody as the English version. No starting tone was given, and participants could choose a comfortable tonality. They were asked to produce two glissandi (a continuous glide from a low note to a high note and vice versa). The aim of these glissandi was multiple: to warm up the vocal organs (22), to help the non-singer to sing the tune in their voice range, to verify the vocal capacity of the subjects which could explain missing notes in the auditory signal, and to encourage a lack of inhibition in front of the experimenter and the recording equipment. The sound recordings were made using a head-worn microphone (Sennheiser HS2) positioned at a constant distance of 2 cm from the right corner of the mouth and a digital recorder (Marantz Professional Solid State Recorder PMD67).

The experienced singers sang 'Happy Birthday' after two glissandi with the instructions to sing 'naturally, whilst imagining a festive and friendly context'. This form of singing is referred to as 'Without a specific vocal Technique' (WT). Thereafter, they sang a phrase from a song in their repertoire in order to warm up for an operatic performance. To finish, we asked them to sing 'Happy Birthday' in an operatic way 'whilst imagining the context of a scene from an opera'. This singing is referred to as 'with Lyrical Technique' (LT). The data were collected using a digital recorder (Zoom nh4) held at a distance of 1 metre away from each participant. The unidirectional microphone was placed directly in front of the mouth of the participant.

Since our study focuses on the interval accuracy and the respect of the tonal centre, we ensured that the tune was the same for all the subjects, whether it concerned the number of notes or the respect of the melodic contour.

Analytical procedure

The equal temperament is a compromise tuning scheme which has been developed for keyboard instruments. The equal tempered system uses a constant frequency multiple between the notes of the chromatic scale. This system seems to not suit a cappella choirs (30,31) but stays a reference in Western music. The acoustic analyses of individual performances of the popular song 'Happy Birthday' were based on this temperament.

The popular song 'Happy Birthday' is made up of four phrases, with each syllable corresponding to a note. It totals 25 notes corresponding to the 25 syllables of the song and 21 when the repeated notes are not taken into account. The vowels provide the maximum of voicing and stable pitch information (32), mark the onsets of musical tones (33), and constitute the best targets for analysis. Thanks to AudioSculpt and OpenMusic (IRCAM, Paris, France), we were easily able to analyse the vowels sung on the 21 notes in two steps, using a MacBook Pro (Mac OS X, version 10.6.5).

The first step involved the use of the AudioSculpt 2.9.4v3 software (designed and developed by the IRCAM Analysis/Synthesis Team). This program enabled various processing and analysis of audio files (.wav). Note that analysis and treatments performed through this software use a short-time Fourier transform (STFT) analysis as an initial step. Therefore, the main parameters of the STFT analysis (window size, window type, FFT size, and window step) can

be modified. For an easy visualization of the auditory signal a sonogram analysis was performed. The window size is the principal factor determining the analysis properties of spectral or partial analysis. It allows to precise the time and frequency resolution of the analysis performed. We have chosen a window size of 2048 samples (it represents 46.42 ms) and a window step of 8. This combination, recommended by experts in computer-assisted music and validated by specialists in music analysis, allows precise analysis of the singing voice.

AudioSculpt permits unharmonic frequencies to be disregarded (subharmonics and noises were selected and rejected) and therefore enables automatic and correct recognition of the partials by the software. Following this step, markers were manually placed on the spectrogram. Attacks were avoided, and the stable parts of each vowel-group were isolated avoiding the slides toward the pitch at the beginning of a note. This step was possible thanks to the precise visualization of the acoustic signal. To help the experimenter, a zoom (focus on a part of the visual representation) or a time stretching (slowing the tempo without changing the spectral information of the sound) can be used. Finally, a chord sequence analysis was performed with similar parameters and allowed a chord to be obtained of all the partials analysed between each marker. The aim was to gain averages for each partial between two markers.

The second step was conducted using the Open Music 6.3 software (designed and developed by the IRCAM Musical Representations Team). This programming tool allowed analysis and processing of musical structures. The program made it possible to skip the segments between two notes (i.e. to consider only the 21 notes of the melody), to select the lowest partial to be analysed, and to transcribe into cents (1/2 tone = 100 cents). This process allowed the averages of the F0 to be obtained for the 21 notes of the tune.

As shown in Figure 2, different objects allowed the final analysis of the acoustic signal. The files (.sdif) of chord analysis were converted into data (AS→OM). Then, only the 21 notes of the tune were conserved (LISP length, arthm-ser and Posn-match), and the lowest partial was selected (list-minimum and OMLOOP). The final analysis could be listened to, visualized on a score, or observed through the list of the notes' pitches (in cents). The file (.txt) was then exported to Excel in order to compute the pitch errors of the sung performance, regarding two different criteria: pitch interval deviation and tonal centre deviation.

Calculations

The average tempo of the singing was calculated on the basis of the performance's length. Two criteria were chosen to estimate the accuracy of the singing: the pitch interval deviation (for pitch interval errors) and the tonal centre deviation (for tonal centre error). In both cases, the criteria were estimated by measuring the difference between the size of intervals performed and the standard size based on the musical notation (Figure 3). A small deviation reflects high
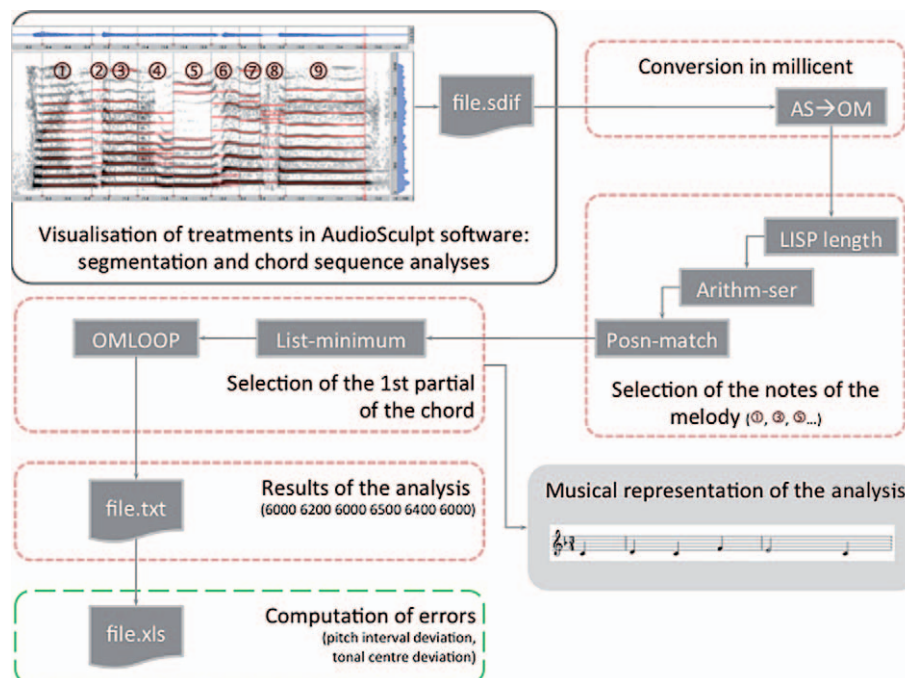

Figure 2. Illustration of the procedure used for acoustic analyses of a sung performance.

Figure 3. Score of the tune 'Happy Birthday' with the number of notes used for calculating accuracy.

accuracy in relative pitch. Note that the measurements were not computed in terms of semitones but on a continuous scale (in cents).

Pitch interval deviation. This measurement has often been adopted as a measure of singing proficiency (e.g. (6,7,9,14)). Each interval was calculated by subtracting the pitch of the adjacent notes. Since the absence of contour errors was a selection criterion for our samples, the intervals could be calculated in absolute values. Each value was compared to a standard (a theoretical value estimated on the basis of the score) and represented in cents. For example, the interval between the second and third note of the tune should form a major second, which corresponds to a variance of 200 cents. If a subject made a quarter-tone mistake, i.e. if she sang an interval of 150 or 250 cents, we considered that the error was 50 cents in relation to the expected interval.

Tonal centre deviation. In terms of the 'tonal centre' criterion, Dalla Bella et al. (7) observed the 'pitch stability' by computing the deviation of two reproductions of a single phrase in a melody. This measurement was not applicable to the song 'Happy Birthday' because of its structure (no repetition in the melody). To evaluate this criterion, we propose here to adapt the 'precision' criterion used in Pfordresher et al. (9). They observed the consistency in repeating targets through imitation tasks of unfamiliar pitch sequences. A popular song is characterized by a strong tonal centre and the presence of important notes of the harmony given by the scale of the tune. In this study we observed the consistency of important notes of the harmony as a measure of the tonal centre deviation. Four notes (the first notes of the three first sentences and the last note, i.e. notes 1, 6, 11, and 21 on Figure 3) were selected. According to harmonic rules of Western music, these four notes establish the tonality centre of the tune and are

considered as important and useful to determine the tonality of the tune. The last tone (note 21) refers undoubtedly to the first degree of the tonality of the song, namely the fundamental tone. The three first phrases begin with 'Happy' and are sung on the same note (notes 1, 6, and 11). This tone can be analysed as the fifth degree of the scale in which the tune is sung, called dominant, or as the fundamental note (first degree) of the dominant seventh chord of the principal tonality. In both cases, these three notes carry important information about the tonality of the melody. Intervals performed between the four notes selected were compared to the standard value, with the same procedure as for the criterion 'pitch interval deviation'. A small deviation reflected a high respect of the tonal centre of the melody.

Results

Means and standard error of tempo, pitch interval deviation, and tonal centre deviation for OS, WT singers, and LT singers are reported in Table I.

A one-way ANOVA was applied to compare the three groups (OS, WT singers, LT singers) and to estimate the difference in averages for the measurements of tempo and accuracy (pitch interval deviation and tonal centre deviation).

As can be seen in Table I, the means for each group were significantly different for the tempo ($F_{(2.88)} = 16.61$, $P < 0.001$), the pitch interval deviation ($F_{(2.88)} = 5.072$, $P = 0.008$), and tended to be different for the tonal centre deviation ($F_{(2.88)} = 3.001$, $P = 0.055$).

The performance tempo was quicker for WT singers ($M = 112.99$ beats per minute, $SE = 4.59$) than for OS ($M = 98.37$, $SE = 1.79$). When the operatic vocal technique was applied, the tempo was slower ($M = 80.13$, $SE = 4.53$) than for the two other groups.

Table I. Measurements describing vocal performance (tempo, interval deviation criterion, tonal centre deviation criterion) according to the group and comparison of averages between the sample groups.

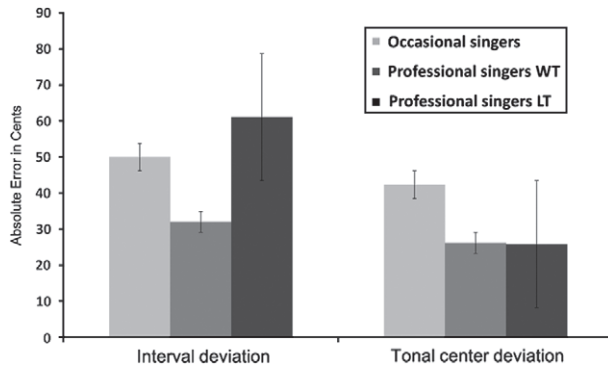|	Descriptive statistics			
	Occasional singers M (SE)	Professional singers WT M (SE)	Professional singers LT M (SE)	One-way ANOVA
Tempo (beats per minute)	98.37 (1.79)	112.99 (4.59)	80.13 (4.53)	$F_{(2.88)} = 16.61$ $P < 0.001$
Interval deviation (absolute error in cents)	50.83 (3.29)	32.81 (2.25)	62.13 (7.66)	$F_{(2.88)} = 5.07$ $P = 0.008$
Tonal centre deviation (absolute error in cents)	42.33 (4.14)	26.17 (3.32)	25.81 (6.17)	$F_{(2.88)} = 3.00$ $P = 0.055$

Figure 4. The average absolute value (in cents) of the interval deviation and the tonal centre deviation criteria for each group (OS, WT singers, LT singers), with standard error bars.

Figure 5. Correlations between the tempo and the interval deviations for the three groups (OS, WT singers, LT singers).

As regards the measurements of accuracy, we conducted repeated measures T tests for the singing of WT and LT singers and independent measures T tests to compare the performances of OS with WT singers (Figure 4).

Regarding the tonal centre deviation, the OS performed worse (M = 42.33, SE = 4.14) than the WT singers (M = 26.17, SE = 3.32) (t = 3.046; P = 0.004) and LT singers (M = 25.81, SE = 6.17) (t = 2.224; P = 0.035). There was no significant difference between the performance of the WT and LT singers.

Regarding the pitch interval deviation, the OS performed worse (M = 50.83, SE = 3.29) than the WT singers (M = 32.81, SE = 2.25) (t = 4.514; P < 0.001), but their performances were not significantly different from those of the LT singers (M = 62.13, SE = 7.66). When the operatic vocal technique was applied, more errors emerged than when the professional singers did not use this vocal technique (t = 4.27, P = 0.001).

As regards correlations between tempo and interval accuracy, we applied the Spearman's rank correlation coefficient to each group of samples in order to observe the correlations between the tempo of the tune and the pitch interval deviation (Figure 5). For the WT singers, no correlation was observed between these two measurements (r(14) = 0.130; P = 0.659), whilst for the OS the accuracy increased when the singing tempo was slow (r(63) = 0.321; P = 0.01). The opposite was true for LT singers. Indeed, the singing was more accurate when the speed was quicker (r(14) = –0.662; P = 0.01).

Discussion

In order to validate our method for analysing the accuracy of a popular song, we analysed the performance of occasional and professional singers. For the occasional singers, we expected to confirm the observations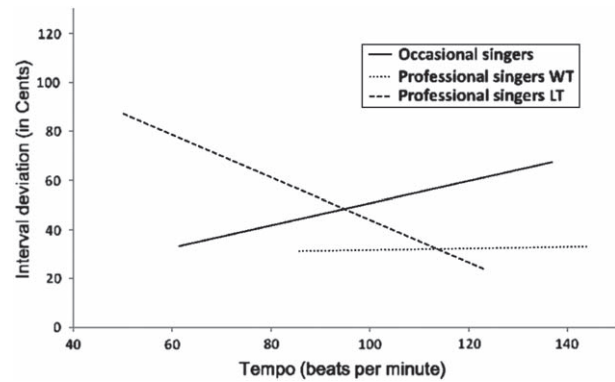 of Dalla Bella et al. (7) about the link between tempo and accuracy, but not for professional singers. In this study, the WT singers sang quicker than the OS. Whereas we observed a correlation between the interval accuracy and the tempo for OS (Figure 5), this correlation did not appear for experienced singers. On average, they had a quicker tempo than the OS, but no link appeared between the speed of singing and the interval accuracy. The opposite is true for LT singers. On average, they sang more slowly than the OS, but in their case the interval accuracy was better when the tempo was increased. We thus encountered in this instance the profile described in the literature (the slower it is, the more accurate it is) for the OS.

When comparing the accuracy of occasional singers who had not received any musical training with that of professionals well-versed in singing techniques, we expected to observe better accuracy amongst the latter and thus back up the relevance of the criteria for accuracy used and the quality of the analytical tools described in this study.

For analysis of accuracy, we chose to focus on the pitch interval deviation and the tonal centre deviation. By eliminating all singing in which contour errors appeared, we limited the cases of 'poor singers'. Nevertheless, the results relating to the tonal centre deviation enabled us to confirm that the OS performed worse than the experienced singers (WT and LT). The effect of vocal expertise expected at this level was clearly visible. The criteria used in our method (first note of each phrase and final note) are therefore relevant, and the type of analysis (lowest partial of the stable part of each vowel group) seems suitable for measurement of the 'tonal centre' criterion.

For the interval accuracy, a difference appeared between the OS and WT singers. The results confirmed that vocal expertise leads to greater interval accuracy. The criterion (comparison of each interval produced with the target interval) as well as the type

of analysis (lowest partial of the stable part of each vowel group) seem suitable for measurement of the 'interval accuracy' criterion.

The possible artefacts reported during the mean F0 estimation (7,9) were not found in our analytical procedure. The AudioSculpt software, used in our method, enabled the deletion of unharmonic frequencies and therefore automatic and correct recognition of the partials by the software. Selecting the lowest partial of segments, and the selected notes of the melody, the OpenMusic software reports automatically the mean F0 for the 21 notes, without any manual intervention. The verification was possible thanks to the musical representation of the results of the analyses.

However, when 'operatic' singing techniques are used, this difference no longer appears, and the pitch interval accuracy is altered. Although we expected a good performance from LT singers, the results do not confirm this. This led us to discuss the criteria and analytical tools for judgement of the accuracy of the singing voice when the operatic vocal technique is applied.

We could not attribute these results to vocal expertise because the precision of intonation is better amongst musicians (7,11,19,20) and also these same singers, without using a specific vocal technique, performed better than the OS.

Two interpretations can explain the results of the LT singers: the pitch interval deviation criterion may not be of paramount importance in judging these voices, and/or our analytical tools may not be suitable for these voices.

Whilst the quality of singing is judged primarily on the basis of intonation (2), it seems that, in an operatic context, this criterion is no longer as evident and that accuracy within the meaning of 'interval accuracy' may only be of secondary importance. Analysis of the accuracy was conducted on the stable segments of each vowel. We did our utmost to control the interpretation by not considering the liaisons between notes in our acoustic analysis. However, even if the composition is respected in classical music, the quality of the singing is also linked to the freedom of interpretation exercised by a singer. He or she intentionally modifies the size of the intervals (and the accuracy of the intervals is thus altered) without, however, modifying the musical phrase (the tonal centre is respected). This freedom of interpretation aimed at reinforcing the musicality may therefore be a criterion that would benefit from better control in future research aimed at objectively analysing the accuracy of singing.

In the case where the interval accuracy remains a criterion of paramount importance for estimating the quality of a vocal performance, the intention of LT singers would be not to alter this precision. Our analytical tools provided averages for the fluctuations of the F0 and therefore calculated an average of vibrato for each note. Some studies highlighted that the pitch of the sound produced with vibrato is perceived as an average of the F0 and that the amplitude of the vibrato does not influence the perception of the sound's pitch (34,35). On the contrary, this fluctuation in frequency is often considered as additional 'colour' and represents a much sought-after characteristic (36). However, more recently, it has been shown that the perceived pitch with vibrato can be influenced by its phase and duration (37), and that a range of acceptable tuning is accepted by the listener (38). In this study, the vibrato used by the LT singers was especially apparent. Here, calculating the average of the fluctuations may not be adequate and should be investigated in future research. Whilst the vibrato contributes to the quality of the sound (39), our results indicate that it represents a bias during objective measurements of the accuracy of singing in a melodic context.

Conclusion

In this study, two criteria (pitch interval deviation and tonal centre deviation) were observed by means of semi-automatic analytical tools. The performances of occasional and professional female singers enabled us to observe the expected effect of vocal expertise on accuracy but also to confirm the profile of occasional singers highlighted in the study by Dalla Bella et al. (7). Whilst the application of an operatic singing technique renders the objective analysis of accuracy unreliable, the analytical tools as well as the criteria used in this study seem perfectly suited for an objective assessment of accuracy of a popular song in occasional and experienced singers.

Acknowledgements

Declaration of interest: The authors report no conflicts of interest.

References

1. Welch GF. Singing as communication. In: Miell D, MacDonald R, Hargreaves DJ, editors. Musical communication. Oxford: Oxford University Press; 2005. p. 239–60.
2. Watts C, Barnes-Burroughs K, Andrianopoulos M, Carr M. Potential factors related to untrained singing talent: a survey of singing pedagogues. J Voice. 2003;17:298–307.

RIGHTSLINK

3. Dalla Bella S, Berkowska M, Sowinski J. Disorders of pitch production in tone deafness. Front Psychol. 2011;2(164):1–11.

4. Welch GF. Poor pitch singing: a review of the literature. Psychol Music. 1979;7:50–8.

5. Henry MJ, McAuley JD. On the prevalence of congenital amusia. Music Percept. 2010;27:413–8.

6. Dalla Bella S, Berkowska M. Singing proficiency in the majority. Ann N Y Acad Sci. 2009;1169:99–107.

7. Dalla Bella S, Giguère J-F, Peretz I. Singing proficiency in the general population. J Acoust Soc Am. 2007;121:1182–9.

8. Pfordresher PQ, Brown S. Poor-pitch singing in the absence of "tone deafness". Music Percept. 2007;25:95–115.

9. Pfordresher PQ, Brown S, Meier KM, Belyk M, Liotti M. Imprecise singing is widespread. J Acoust Soc Am. 2010; 128:2182–90.

10. Hutchins S, Peretz I. A frog in your throat or in your ear? Searching for the causes of poor singing. J Exp Psychol Gen. 2012;141:76–97.

11. Amir O, Amir N, Kishon-Rabin L. The effect of superior auditory skills on vocal accuracy. J Acoust Soc Am. 2003; 113:1102–8.

12. Watts C, Moore R, McCaghren K. The relationship between vocal pitch-matching skills and pitch discrimination skills in untrained accurate and inaccurate singers. J Voice. 2005;19: 534–43.

13. Wise KJ, Sloboda JA. Establishing an empirical profile of self-defined "tone deafness": perception, singing performance and self-assessment. Music Sci. 2008;12:3–26.

14. Berkowska M, Dalla Bella S. Reducing linguistic information enhances singing proficiency in occasional singers. Ann N Y Acad Sci. 2009;1169:108–11.

15. Boersma P. Praat: a system for doing phonetics by computer. Glot Int. 2001;5:341–4.

16. Boersma P, Weenink D. Praat: doing phonetics by computer (Version 5.1.05) [Computer program]. Retrieved May 1, 2009, from http://www.praat.org/

17. Zatorre RJ, Chen JL, Penhune VB. When the brain plays music: auditory-motor interactions in music perception and production. Nat Rev Neurosci. 2007;8:547–58.

18. Kraus N, Chandrasekaran B. Music training for the development of auditory skills. Nat Neurosci. 2010;11:599–605.

19. Murry T. Pitch-matching accuracy in singers and non-singers. J Voice. 1990;4:317–21.

20. Watts C, Murphy J, Barnes-Burroughs K. Pitch matching accuracy of trained singers, untrained subjects with talented singing voices, and untrained subjects with nontalented singing voices in conditions of varying feedback. J Voice. 2003;17:185–94.

21. Wilsonarboleda B, Frederick A. Considerations for maintenance of postural alignment for voice production. J Voice. 2008;22:90–9.

22. Amir O, Amir N, Michaeli O. Evaluating the influence of warmup on singing voice quality using acoustic measures. J Voice. 2005;19:252–60.

23. Sundberg J. The science of the singing voice. DeKalb: Northern Illinois University Press; 1987.

24. Sundberg J. The perception of singing. In: Deutsch D, editor. Psychology of music. San Diego, CA: Academic Press; 1999. p. 171–214.

25. Reid K, Davis P, Oates J, Cabrera D, Ternstrom S, Black M, et al. The acoustic characteristics of professional opera singers performing in chorus versus solo mode. J Voice. 2007; 21:35–45.

26. Brown WSJ, Rothman HB, Sapienza CM. Perceptual and acoustic study of professionally trained versus untrained voices. J Voice. 2000;14:301–9.

27. Hunter EJ, Svec JG, Titze IR. Comparison of the produced and perceived voice range profiles in untrained and trained classical singers. J Voice. 2006;20:513–26.

28. Mendes AP, Rothman HB, Sapienza C, Brown WSJ. Effects of vocal training on the acoustic parameters of the singing voice. J Voice. 2003;17:529–43.

29. Vurma A, Ross J. Production and perception of musical intervals. Music Percept. 2006;23:331–4.

30. Howard DM. Equal or non-equal temperament in a capella SATB singing. Logoped Phoniatr Vocol. 2007;32: 87–94.

31. Howard DM. Intonation drift in a capella soprano, alto, tenor, bass quartet singing with key modulation. J Voice. 2007;21:300–15.

32. Murayama J, Kashiwagi T, Kashiwagi A, Mimura M. Impaired pitch production and preserved rhythm production in a right brain-damaged patient with amusia. Brain Cogn. 2004;56: 36–42.

33. Sundberg J, Bauer-Huppmann J. When does a sung tone start? J Voice. 2007;21:285–93.

34. Shonle JI, Horan KE. The pitch of vibrato tones. J Acoust Soc Am. 1980;67:246–52.

35. Sundberg J. Effects of the vibrato and the «singing formant» on pitch. J Res Sing. 1978;5:5–17.

36. DeLeo LeBorgne W, Lee L, Stemple JC, Bush H. Perceptual findings on the Broadway belt voice. J Voice. 2010;24: 678–89.

37. van Besouw RM, Brereton JS, Howard DM. Range of tuning for tones with and without vibrato. Music Percept. 2008;26: 145–55.

38. van Besouw RM, Howard DM. Effects of carrier and phase on the pitch of long-duration vibrato tone. Musicae Scientiae. 2008;8:139–61.

39. Sundberg J. Perceptual aspects of singing. J Voice. 1994;8:106–22.