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Role of Proprioceptive Memory in a Professional Opera Singer's Absolute Pitch

An Experimental Pilot Study

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Abstract: *This experiment was aimed at modifying the proprioceptive references of a professional soprano endowed with absolute pitch. To do so, an osteopathic doctor changed the height of her larynx by altering the tension between the hyoid bone and the occipital bone. A cephalometric analysis of x-rays taken before and after the manipulations indicated that the position of the phonatory organs had indeed been affected. The results of an acoustic analysis, and perception tests on the tones produced before and after manipulation provided irrefutable evidence of the influence of the laryngeal manipulations on the tonal accuracy of the emission. This study demonstrates the critical role that this soprano's kinesthetic-pallesthetic memory plays in pitch recognition, and suggests the existence of different types of absolute pitch.*

Keywords*: Singing voice, Laryngeal height, Tonal accuracy, Kinesthetic and pallesthetic reference sensitivities, Internal tuning fork, Tuning strategy, Absolute pitch, Proprioceptive memory.*

Introduction

Given the complexity of the topic and the difficulty of conducting experiments in this area other than via MRI or EEG, experimental research on absolute pitch deals mainly with the brain functioning of musicians who possess this ability (increased size of the *planum temporale* [1] study of the endogenous evoked potential [2] of P3 [3], etc). In parallel, a few studies have attempted to discover the genes involved in the development of absolute pitch [4]. While all of these studies focus on the genesis of the phenomenon, the present research attempts to gain insight into how absolute pitch functions by analyzing an opera singer's tuning strategy.

Opera singers possess an extremely precise kinesthetic memory of the positions of their phonatory organs when singing each tone in their tessitura.

A preliminary experiment on the reproducibility of phonatory positions in opera singing was first conducted on six volunteer professional singers, including the soprano who participated in the study. One or two months apart, depending on availability, two series of x-rays were taken of the singers as they sung the same note, on the same vowel, in the lower register and then in the upper register, two octaves higher. A comparison of the x-rays of each singer in each register indicated no apparent difference over time, and the X-ray tracings, when superimposed, were almost perfectly aligned. Such positional precision during phonation may seem surprising, but as we shall see in this study, although the manipulated organs moved very slightly both for the linear and the angular measures, the shifts led to fully audible differences in timbre and vocal quality. Given that one of the priorities of singers is to achieve voice homogeneity, it is normal that they strive for extreme precision in the positions and movements of their phonatory organs.

Most of those who possess absolute pitch — that is, the ability to spontaneously recognize or produce any tone without an external reference— utilize a strategy which suggests that their proprioceptive memory acts as an internal tuning fork. It was hypothesized here that the sheer fact of changing the position of one of the phonatory organs would disrupt the proprioceptive control of tone accuracy. An experiment was conducted to test this hypothesis.

Experiment

The professional soprano chosen for the study, who is endowed with absolute pitch, uses a vocal technique based on internal voice sensitivities (IVS) and involving a slight downward shift of the larynx for singing in the lower register and a slight upward shift for singing in the upper register, which is a characteristic of high, vocalizing voices. The experiment was aimed at modifying the proprioceptive references of this singer. This was achieved with the collaboration of an osteopathic doctor, who performed a series of manipulations consisting in altering the tension between her hyoid and occipital bones and thereby modifying the height of the larynx.

The experiment was conducted in accordance with ethical standards, and with the consent of the Head of the Adult

Radiology Department at the Timone University Hospital in Marseilles. The most up-to-date radiology equipment was used. At each step of the experiment, every methodological precaution was taken to protect the singers from any kind of physical or moral harm. Moreover, the osteopathic manipulations were pre-tested on the author, and the radiology equipment settings were pre-adjusted in such a way that the singers who volunteered to take part in the experiment would be exposed to the lowest possible level of radiation.

Experimental Setup

Profile x-rays of the head and neck in left/plate position (distance: 3 meters, duration of exposure: 0.15 s, voltage: 120 kv, current: 100 mAS) were taken before and after manipulation, using an antidiffusion system. The subject was standing and was allowed to assume a natural position without any constraints (such as the use of a cephalostat, or positioning in the Frankfort Plane by the radiologist). In order to be able to analyze the soprano's comments and perform the acoustic study of her voice quality before and after manipulation, the entire session was recorded on a professional Nagra DR-S recorder equipped with an omnidirectional Sennheiser ME40 microphone. To avoid influencing her analysis of what she was feeling, she was not informed of the true reason for the manipulations she would undergo.

Experimental Procedure

To obtain reference x-rays and recordings before the osteopathic doctor performed the manipulation, the soprano was asked to sing her entire tessitura from the lower to the upper register, and then to sing the vowel [a] in the lower register on Bb_3 (233 Hz) and in the upper register on Bb_5 (932 Hz). A profile X-ray was taken for each of these two tones, with simultaneous recording of the sound. Next, the practitioner had the subject lie down. He controlled the position of the temporal occipital bone with one hand, and of the hyoid bone with the other. The first part of the preparation phase required balancing the tensions. To do this, he began by holding the occipital bone in a fixed position and slightly drawing the hyoid bone forward; then he held the hyoid bone in a fixed position and slightly pushed the occipital bone backward. The second part required finding a point of equilibrium between these two extremes, which relaxes the tissues and enables the proper arrival of blood, lymph, and interstitial tissues. Only at this point can the manipulation be performed. Two approaches are possible: the practitioner can either change the hyoid bone tension relative to the occipital bone, or change the occipital bone tension relative to the hyoid bone. The second solution was chosen because it is closer to physiological reality. In this case, the doctor acts upon the occipital bone, either by moving the hyoid bone downward and thereby preventing the larynx from rising, which corresponds to the laryngeal position used by this soprano to sing in the lower register, or by moving it upward and thereby preventing the larynx from lowering, which corresponds to the laryngeal position she uses to sing in the upper register.

Then the first manipulation was performed to set the singer's larynx in the lower-register position via the anteriorization of her occipital bone. This was achieved by sliding the occipital condyle along the glenoid cavity of the atlas in such a way that the posterior surface of the odontoid apophysis of the axis came closer to the posterior part of the *foramen magnum*. This occipital bone position causes the anteriorization of the styloid apophysis of the temporal bone, which releases stylohyoid muscle tension and lowers the hyoid bone and the larynx. The experiment must be completed within the next ten minutes, after which the phonatory organs return to their initial position. In this low-larynx position, the soprano was asked to sing the vowel [a] in her upper register (on Bb_5) as a profile X-ray was being taken and her voice was being recorded. Then she was asked to sing across her tessitura from the lower register to the upper register, and to state her impressions.

The same process was used for the second manipulation, which set the subject's larynx in the upper-register position. This time, the manipulation consisted in posteriorizing the occipital bone relative to the atlas, in order to trigger a superior-posterior shift of the styloid apophysis and thereby increase the tension of the stylohyoid muscle, causing the hyoid bone to pivot upward and backward and the laryngeal box to rise.

Physiological and Acoustical Analysis Results

Method

The four x-rays of the vowel [a], i.e., in the lower register on Bb_3 and in the upper register on Bb_5, before and after manipulation, were analyzed using a method derived from cephalometry [5] and adapted to the radiological study of phonation [6]. For this analysis, 31 parameters were measured: head position, anterior-posterior movements of the cervical spine, craniocervical angle, buccal opening, labial opening, lip projection or retraction (upper and lower), lip thickness (upper and lower), lip height (upper and lower), tongue mass orientation, aperture, region of articulation, velar tension, degree of nasalization (at the pharyngo-uvular level) and buccalization (at the dorso-uvular level), vertical and anterior-posterior movements of the hyoid bone and its tilt, thyrohyoidian space, vertical and anterior-posterior movements of the thyroid cartilage and its tilt, vertical and anterior-posterior movements of the cricoid cartilage and its tilt, pharyngeal cavity dimensions at its maximal constriction points (at rhinopharyngeal, buccopharyngeal, and hypo-pharyngeal levels), and vocal tract length (Fig. 1).

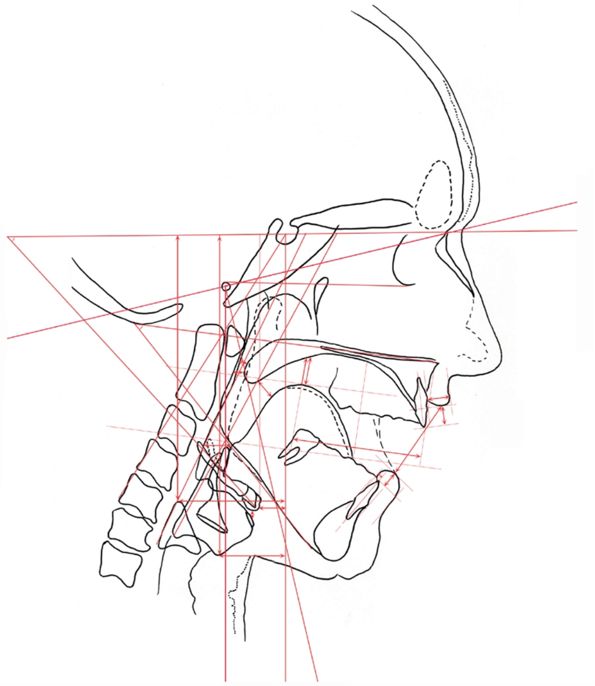

Figure 1

Measures

Given that the minute movements of the manipulated organs required extremely precise measures, we produced a 5 x 5 mm calibrated plate of the radiographically-opaque distortion grid under strictly identical conditions to those used for x-raying the soprano. The analysis of this plate gave us scaled measures that took into account any magnification or deformation resulting from the angle at which the x-rays hit the plate. Insofar as the values used were corrected to compensate for the rates of magnification and distorsion inherent in the radiographic process, the results presented in this study correspond to real values, not measured ones.

First Manipulation

Anamnesis

After the first manipulation aimed at setting the larynx in the lower-register position, the subject said that she felt "pulled downward" and was experiencing difficulty singing in the upper register. Moreover, the acoustic analysis confirmed these statements by revealing the poor quality of the high-pitched tones produced.

Cephalometric Analysis

A comparison of the radiographic tracings of the vowel [a] sung in the upper register on Bb_5 before and after manipulation pointed out:

- *Phonatory positions specific to lower-register emission*
  * anteriorization of the cervical spine (Δ = + 3.6 mm)
  * decrease in velar tension (Δ = + 1.8 mm)
  * anteriorization of the tongue mass (Δ = - 3 mm)
  * lowering (Δ = - 1 mm) and anteriorization of the laryngeal box (Δ = + 7.7 mm)
  * less pronounced hyoid tilt (Δ = - 4°)
  * less pronounced thyrocricoidian tilt (Δ = - 7°)
- *Phonatory positions specific to upper-register emission:*
  * nearly identical thyrohyoidian space.
- *Compensating phonatory positions*
  * smaller labial opening (Δ = - 9 mm)
  * smaller buccal opening (Δ = - 2.9 mm)
  * slight tilt of the head (Δ = - 2°).

Physiological Interpretation

The lowering of the laryngeal box caused by the manipulation resulted in a vocal-tract volume increase that required the subject to make an acoustic adjustment in order to sing in the upper register [7]. She achieved this by reducing the mandibular opening in order to decrease the volume of the buccal resonator and compensate for the upper-lip spreading brought about by the considerable rise in the cheeks, one of this soprano's characteristic facial expressions for upper-register singing.

The head tilt angle with respect to the Frankfort Plane was 2° after the manipulation. The singer tried to counteract the resulting occipital anteriorization by lowering her head. This raised and posteriorized her occipital bone and its styloid apophysis, which moved the hyoid bone upward and backward and thereby facilitate the thyrocricoidian shift required in the upper register [8]. Without this compensatory maneuver, which enabled her to raise the "place" of her voice, the soprano said she would have been unable to produce this high-pitched tone. (Fig. 2a)

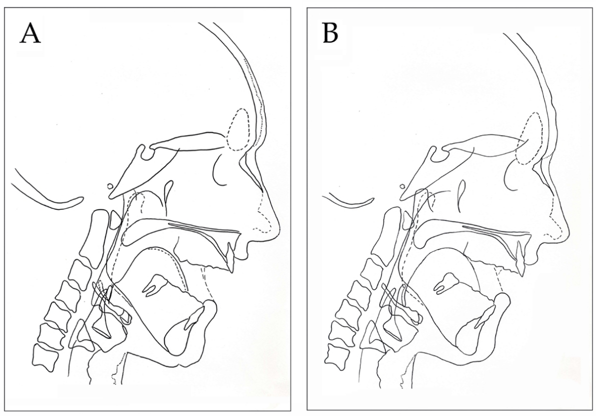

Figure 2 a

Sonagraphic Analysis and Acoustic Interpretation

The acoustic part of this study was based on the corpus that was recorded while x-rays were being taken of the soprano singing the vowel [a] in the lower and upper registers, before and after manipulation. The following calculations were made for each sound: onset accuracy, hold accuracy, the accuracy difference between the onset pitch and the target pitch (i.e., the theoretical frequency of the reference note), between the hold and the target, between the onset and the hold, between the onset before and after manipulation, and between the hold before and after manipulation. Timbre (spectral composition) and vibrato (amplitude, periodicity, regularity quotient, latency, and stabilization time) were also analyzed.

Comparison of the sonagrams of the vowel [a] sung in the upper register on Bb_5 before and after manipulation revealed a drop of 14.87 Svt (≈ 1/4 of a tone) on the Bb_5 onset after manipulation. The mean pitch calculated on the total duration of the hold decreased by 10.56 Svt (≈ 2 commas). This was caused by lowering of the laryngeal box, along with a less pronounced crico-thyroidian shift. The low laryngeal position also had an impact both on the note's timbre, which was darker due to the paucity of the high-frequency harmonics (attenuation of harmonics starting at H4), and on the placement of the sound, which was less cephalized, less "in the head" than the reference sound.

The manipulation had little effect on the vibrato. Its periodicity went from 6.72 to 6.30 Pv/s and its amplitude, from 47.75 to 38 Svt. The mean regularity quotient was virtually identical before (22.22%) and after (23.30%) manipulation. In both cases, the vibrato was irregular. The vibrato latency and stabilization time were significantly longer than in the reference sound, since they practically doubled in duration. Latency rose from 22.50 cs to 32.10 cs and stabilization time, from 63 cs to 135 cs, indicating that following manipulation, the soprano had trouble finding the correct pitch of the sound (Fig. 2b)

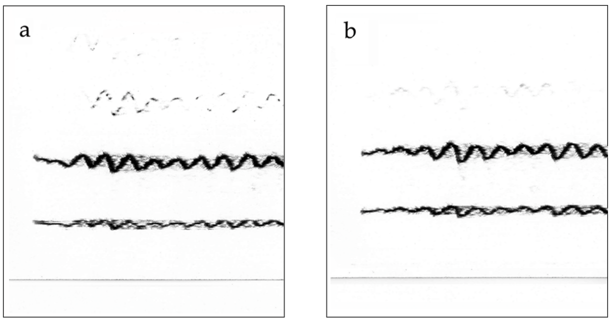

Figure 2 b

In summary, the Bb_5 after manipulation was two commas lower than the one sung before. It also was "placed lower", was less of a *head tone*, and had a slightly darker timbre than the reference sound.

Second Manipulation

Anamnesis

After the second manipulation aimed at setting the larynx in the upper-register position, the singer said that the high-pitched tones were easier to produce, although she experienced no additional difficulty with lower-register ones. The acoustic analysis confirmed an excellent vocal quality across the lower-to upper-register range.

Cephalometrics Analysis

The comparison between the radiographic tracings of the vowel [a] sung in the lower register on Bb_3 before and after manipulation pointed out:

- *Phonatory positions specific to upper-register emission*
  * *slight posteriorization of the cervical spine (Δ = - 0,1 mm)*
  * posteriorization (Δ = - 0.7 mm), elevation (Δ = + 1.6 mm), and verticalization of the hyoid bone (Δ = + 4°)
  * rise of the laryngeal box (Δ = + 3 mm)
  * decrease in the thyrohyoidian space (Δ = - 0,2 mm)
  * greater thyrocricoidian shift (Δ = + 3°)
  * wider pharyngo-uvular space (Δ = + 2 mm),
  * slightly less labialization (Δ = - 1 mm)
  * shortening of the vocal tract (Δ = - 5 mm)
- *Phonatory positions specific to lower-register emission*
  * nearly identical tongue position
  * nearly identical velum position
- *Compensating phonatory positions*
  * smaller buccal opening (Δ = - 1,4 mm)
  * smaller labial opening (Δ = - 3.8 mm),

Physiological Interpretation

Because lower-register emission does not require mobilization of the phonatory organs as much as upper-register emission, the soprano did not have any major problems singing in the lower register with her larynx positioned for the upper register. This accounts for why her compensating phonatory positions were limited to an attempt to correct the vowel's timbre by reducing the buccal opening and the labial opening. Indeed, the smaller vocal-tract volume resulting from the second manipulation required an acoustic adjustment aimed at darkening the timbre in the lower register. To do this, the vocal tract could be lengthened by substantial labial projection and its volume could be decreased by reducing the buccal opening. While the buccal opening was not as great as it was on the reference sound, it was not narrow enough to meet acoustic requirements. Concerning labial projection, its extent was almost identical here to that used before the manipulation, most likely because this position is the singer's physiological limit. The soprano attempted to compensate for the insufficient labialization and the inappropriate buccal opening by reducing her labial opening (Fig. 3a)

Sonagraphic Analysis and Acoustic Interpretation

After manipulation, the Bb_3 onset was 57.04 Svt higher (more than one tone). The hold was up 25.98 Svt (1/2 tone) compared to the control tone. This can be explained by the rise of the laryngeal box and a more pronounced crico-thyroidian shift. Moreover, this laryngeal position had an impact on timbre, which was clearer due to its rich high-frequency harmonics (reinforcement of H7, H8, H10, H13, H15, and H16), and on the placement of the sound, which was less of a *chest tone* than the reference [9].

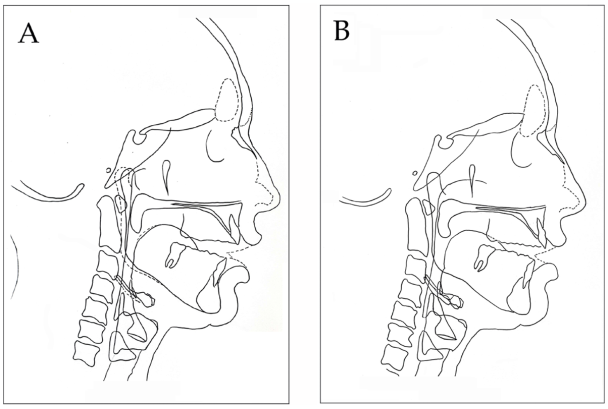

Figure 3 a

Looking now at the vibrato, although its amplitude decreased slightly (-3 Svt) after manipulation, its periodicity hardly changed (5.84 instead of 5.82 Pv/s). On the other hand, it lost its regularity, with the mean regularity quotient rising from 12.5% for the control tone (regular vibrato) to 29% for the post-manipulation tone (irregular vibrato). Curiously, the pre-manipulation latency of 37.20 cs dropped to 19.95 cs afterwards. The time taken by the vibrato to set in here was twice as short after manipulation, even though the "destabilized" soprano should have taken more time to find the right pitch before beginning to make the sound vibrate. It is no doubt because of this abnormally short latency that she needed four times as much time to stabilize her vibrato. Indeed, her stabilization time, which was 37.20 cs for the control tone, rose as high as 172.50 cs after manipulation (Fig. 3b).

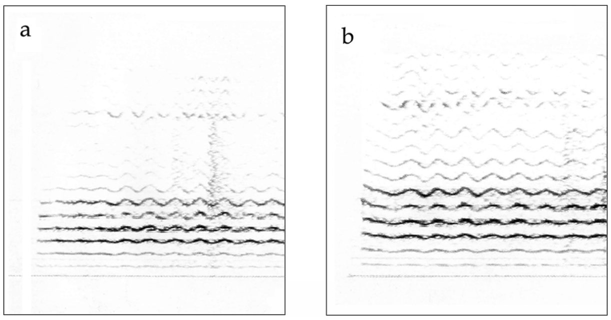

Figure 3 b

In summary, the Bb_3 sung after the manipulation was a semi-tone higher than beforehand. Moreover, it sounded less like a chest tone and thus possessed a much lighter timbre than a low-pitched tone produced by this soprano under normal conditions.

Results of the Perception Study

Selecting Listeners

A perceptual study of the Bb_3 and Bb_5 sung before and after manipulation was conducted on 10 musicians (GI) who rated only accuracy, and on 5 singing teachers and 5 professional singers (GII) who rated accuracy as well as voice placement. The soprano who had undergone the manipulations eight months earlier was also asked to rate her own productions, although without being told what experiment was at stake (GIII). All subjects selected (GI, GII, and GIII) underwent a preliminary audition test aimed at measuring their pitch differential threshold. Whereas for pure sounds this threshold is about 1.3 Svt (0.26 commas) in non-musicians, in the musicians tested, it was about 0.12 Svt (0.0028 commas), their pitch threshold being 0.7 Svt (0.14 commas) for straight sounds and 4.6 Svt (0.92 commas) for vibrated sounds with an amplitude of 25 Svt (1/2 tone) or less [10].

Testing

The listeners were presented with two pairs of tones: LRBM vs. LRAM (lower register before manipulation vs. lower register after manipulation), and URBM vs. URAM (upper register before manipulation vs. upper register after manipulation). In addition, the second terms of the pairs were interchanged to obtain pairs LRAM vs. LRBM and URAM vs. URBM). The instructions were to compare the second tone to the first one in each pair in terms of accuracy, i.e., they had to judge whether the second tone was higher than, equal to, or lower than the reference tone. The stimuli were assembled loops containing ten randomly ordered repetitions. All 20 listeners who judged tonal accuracy responded unanimously (i.e., all on-key tones were unanimously judged to be on-key and all off-key tones were judged to have the same tonal deviation relative to the target tone). The ten listeners in Group 2 and the listener in Group 3 also responded unanimously regarding voice placement, except for a few minor differences in wording. The listeners also performed a frequency-tuning test consisting of using a frequency generator to equate the different tones recorded. This enabled them to more precisely quantify the tonal inaccuracies they had noted during the first part of the test.

Additional Test

The soprano who had served as the subject was given an additional test consisting in evaluating her own productions by ear (by naming the tone heard). The tones to be judged were assembled on tape in random order and interspersed with ten tones from the reference recording made before the manipulations. There were no repetitions and the subject was tested once. All the tones produced after manipulation were judged to be "horribly" off-key by the soprano.

Evaluation of Vibrated Tone Accuracy

All subjects tested — including the soprano — estimated the low-pitched tone (Bb_3) to be a quarter tone too high and the high-pitched tone (Bb_5), one comma too low. Yet the results of the acoustic analysis on these two notes showed that after manipulation, the Bb_3 was a semi-tone high and the Bb_5 was two commas low. The subjects thus correctly perceived the accuracy errors but underestimated them. This lack of accuracy in pitch assessment, which may seem surprising for professional musicians endowed with an excellent musical ear, is due to the fact that the stimuli they heard were vibrated. Indeed, vocal vibrato consists of periodic frequency variations around a target note. These variations, which range between a quarter tone and three quarters of a tone for a normal voice and may reach or even surpass a whole tone for pathological voices, constitute the amplitude of the vibrato. The greater this amplitude, the more difficult it is for the ear to make a tone judgement [10]. This is why, on the pitch differential threshold tests, the musicians' score fell from 0.12 Svt for pure sounds to 4.6 Svt for vibrated sounds less than or equal to 25 Svt (1/2-tone amplitude). The pre- and post-manipulation stimuli presented to the musicians ranged in amplitude between 38 and 45.75 Svt, so all of these tones had an amplitude above a semi-tone. This accounts for the incorrect tonal-accuracy estimates.

Conclusion

This study showed, firstly, that vocal technique is the result of powerful reflex conditioning, insofar as the height of the laryngeal box automatically determines the singer's phonatory positions. This means, for example, that when the larynx is positioned for singing in the lower register, the organs take on the phonatory positions specific to that register, even during the emission of high-pitched tones and *vice versa*. This study also pointed out the important role that proprioceptive memory plays in pitch recognition for the subject studied here, and thus suggested the existence of different types of absolute pitch. This soprano is endowed with a form of absolute pitch which, unlike that of most instrumentalists, does not call upon auditory memory. Instead, she relies on kinesthetic memory (memory for muscle movements) which is highly developed in opera singers, and thus on pallesthetic memory (memory of vibratory sensations) since differences in the position of the larynx induce different pallesthetic sensations. It is her kinesthetic-pallesthetic memory that enables this singer — via the mental positioning of her phonatory organs — to find the exact pitch of the tones she must recognize or sing. If for any reason the position of these organs is disrupted, she loses her ability to correctly assess pitch and can no longer control the tonal accuracy of the notes she produces.

Absolute pitch is currently considered to rely on a highly exceptional auditory memory. The predominant role of proprioceptive memory shown in this study suggests that other sensory references may be at play in the mechanisms underlying this ability, a topic worth investigating in future research.

Acknowledgments

I would like to express my gratitude to the cantatrice Mady Mesplé who kindly agreed to act as the subject in this experiment. Thanks are also extended to Bruno Fadié, osteopathic doctor, without whom this study could not have been conducted, and to Doctor Patrick Sarrat, radiologist and Patrice Napoletano, X-ray technician at the Timone Hospital in Marseille, France, for their assistance. Special thanks to Vivian Waltz, scientific translator, for the English version of this text.

In memoriam

In memory of my cousin Félix Fabre (1913 - 2001) who, by opening my eyes as a child to the wonders of the world and the mysteries of life, aroused in me the curiosity of the mind, the driving need to learn, to understand, and to explain, which led me to my vocation as a researcher.

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