Comparing the imitating capabilities of parrots and crows with human beings using COMSOL Multiphysics

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Speech signal is a natural means of communication. It uses small units of sound to convey feelings and messages. Birds also use sound signals to express their emotions. Some birds, like parrots and crows, are capable of imitating the speech of other animals. The aim of this study is to compare the imitating capabilities of these birds with those of human beings. The software COMSOL Multiphysics has been used for investigating the effect of dimensional modifications of the vocal tract on the system output. The analysis of the results shows that the acoustic spaces used by human beings, parrots and crows are not overlapping, but similar in shape. Further, maximum formant scattering is observed in human beings and minimum for parrots. The results may be important for understanding the vocal tract modulation, for example, to generate artificial food calls to assemble the birds for feeding medicines to avoid spread of diseases, specifically by parrots and crows as they try to settle down near human civilizations.

Keywords: Birds calls, cardinal vowels, imitation, speech production.

SPEECH consists of small units of sounds and is the only convenient method of communication among human beings. Speech signal seems to be random, but is rich in information. It exploits frequency modulation, amplitude modulation and time modulation to convey information about the identity of the speaker (age and sex), social status, accent, emotion and even his/her state of health[1]. Like human beings, birds also use sound signals to communicate[2–4]. The sound signals used by birds may be classified into calls and songs. The calls are of short duration, unmusical signals and less complex than songs. Calls are produced by both males and females for immediate contact, announcing their location, keeping in touch while flying, alarming threats and sharing information about food sources. Songs are musical, complex and longer compared to calls. Songs are usually sung by males. The function of the song may be an advertisement of their territory, to attract females and to compete with other males.

Parrots (Indian ringneck, Alexandrine, African grey parrots, etc.) and crows are reported to be capable of imitating the speech of other animals[5–8]. Indian ringneck parrots are 37–42 cm long including the tail length of 15–18 cm (refs 5, 6) and weighs around 120–140 g. Syrinx of parrots, the sound-initiating organ, consists of a pair of vibrating membranes; it is simple compared to the syrinx of other birds[9]. Parrots can modulate their tongue, enabling them to produce a variety of sound signals of varying spectral content[10,11]. The surface of the tongue of parrots and human beings is similar in shape and consists of many intrinsic muscles[12]. A variety of parrots are known to mimic the speech of human beings. African grey parrot is able to follow the front–back adjustments of a speaker's tongue, but lacks in following the high–low dimensions[11,13]. Warren *et al.*[13] have reported the change in physical parameters, i.e. opening and closing of the beak for different sounds produced by parrots. It was reported that the sound /a/ can be produced with the beak closed, but /i/ cannot be produced with the same. Frequency and amplitude modulation can be carried by horizontal movement of the tongue, resulting in different types of acoustic patterns while making calls[14]. Several researchers have confirmed the capability of parrots in imitating human beings[15]. Recently, the imitating capacities of Alexandrine parrots have been reported by Singh *et al.*[16]. These parrots were reported to produce long speech sounds by maintaining steadiness in their vocal tract.

Crows are known to be the most adaptable, bold and extremely intelligent birds[5,17]. They are found all over the world, except Antarctica. They are also known for their problem-solving skills, tools making and communication skills. Indian house crows are about 44 cm long with a wing span of 76–85 cm and weigh 300–400 g. The males and females look alike, but males are slightly larger in size[5,18]. Skulls of American crow have average length of 8.6 cm and weight 2.8 g (ref. 19). The tip of the its tongue is naturally split into 1–2 mm (ref. 19). Few crows are known for learning to talk. In the jaw of the birds,

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only the upper bill can move. Crows have cognitive ability similar to that of chimpanzees[20]. They have similar intelligence and behaviour as opposed to magpies (*Pica pica*) which have shown higher self-recognition capabilities[21].

Reaume[19] reported that the American crow has 23 different calls. Crows are known to mimic several animal sounds in the wild[19]. They are able to reproduce the cry of a child, the squawk of a hen and the call of a young rooster[22]. They are also efficient in imitating the sound of dogs, chickens and human beings[8,23]. They are also reported to mimic certain words and phrases spoken by human beings[8,24].

These birds, particularly crows, settle down near human habitats and hence may pose several problems[25]. They are also known to transmit pathogens, affecting people and domestic animals[26,27]. These species are also reported to be carriers of cholera, dysentery, West Nile virus[26,28] and bird flu[29,30]. Hence, it is important to understand their communication behaviour, particularly imitating capabilities to avoid unwanted accidents. Here, we compare the imitating capabilities of parrots and crows with human beings using the software COMSOL Multiphysics.

Sound production mechanism

Lungs are the respiratory organs in human body which help in the manipulation of the pressure and pushing the air pressure towards the trachea[1,31–33]. The change in pressure occurs with the change in shape of the lungs, which is proportional to the breathing in and breathing out mechanisms. The pressure in pushing the air towards trachea is responsible for production of sound due to vibration of the vocal cords. The pitch frequency, the fundamental frequency of vibration of the vocal cords, depends upon several factors, e.g. tension exerted by the muscles, mass and length. Human vocal tract is a complex system of pharynx, tongue, palate, lips and jaw which work together to produce sound signals. It measures about 17 cm for men, 15 cm for women and 14 cm for children. The cross-sectional area varies from 0 to 20 cm^2 under the control for vocalization[34]. Different types of sound signals are produced according to the position of various articulators.

The sound production organs in birds are almost similar as to humans, except for the beak. Lungs, bronchi, syrinx, trachea, larynx, mouth and beak, called articulators, are the main organs of sound production in birds[35–38]. Sound is produced by the flow of air pressure during expiration through an organ called the syrinx. It is situated at the junction of trachea and the two primary bronchi (Figure 1). The pressurized flow of air from the bronchi to trachea helps the tympaniform membranes (TM) present on the medial wall of the bronchus to generate sounds. When air pressure moving from the lungs to the trachea through the bronchi vibrates TM, resulting in sound signals. The frequency of sound signals depends on the vibrations of the TM and amplitude is controlled by air pressure. The function of syrinx in birds is the same as that of vocal cords in human beings. The shape of the syrinx varies with species. The vocal tract modulates the sound or excitation to the vocal tract produced by the syrinx. Some birds sing songs or produce calls by modulating the vocal tract. The width of the beak opening modulates the spectral content[39]. There is some degree of coupling between the syrinx and the vocal tract during production of sounds by the birds[37].

Mathematical models for acoustic analysis of vocal tracts

Only a few researchers attempted to model the vocal tract of birds[40–43]. Fletcher and Tarnopolsky[40] modelled the bird's vocal tract assuming that excitation is provided by the vibrating membrane at its natural frequency leading to air column resonance in the bronchi. Membrane motion changes the cross-section area of the bronchi resulting in the nonlinear propagation of acoustic waves. Fletcher and Tarnopolsky[40] provided an equation

$$p_1 = p_0 + \frac{\rho}{2}\left[\left(\frac{U}{2ru}\right)^2 + \frac{1}{\sqrt{2ru}}\frac{\mathrm{d}U}{\mathrm{d}t}\right], \tag{1}$$

where p_1 is the pressure at the tracheal side of syrinx, p_0 the pressure on the bronchial side of syrinx, ρ the air density, u the displacement in the membrane calculated as a

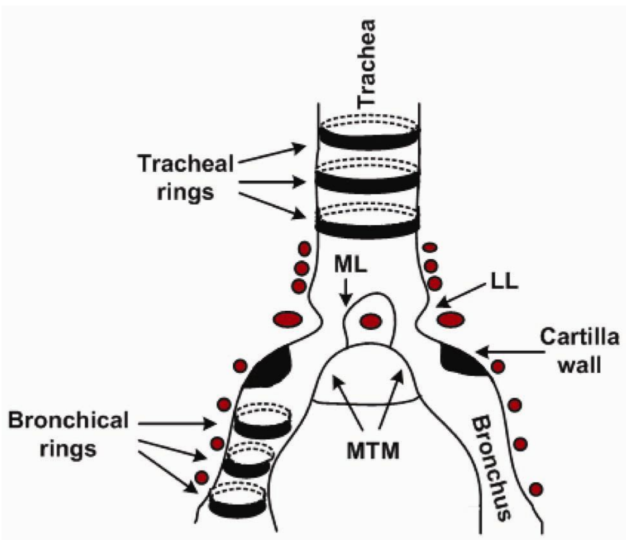

Figure 1. Schematics of a typical bird syrinx. Sound is produced by vibrations of the medial tympaniform membrane (MTM). Structure consisting of medial labia (ML) and lateral labia (LL) acts similar to vocal folds of human beings[51].

function of the driving force F, r the radius of the bronchus and U is the air flow through syrinx which depends on breathing. The displacement membrane is modelled as a simple taut membrane and the displacement F calculated as a function of driving force

$$m\left[\frac{\mathrm{d}^2u}{\mathrm{d}t^2}+2k\frac{\mathrm{d}u}{\mathrm{d}t}+f^2(u-u_0)\right]=\varepsilon F, \tag{2}$$

where f is the mode frequency, k the damping coefficient, m the effective mass of the membrane associated with the mode and u_0 is the position of the membrane at rest. ε is small constant term, which is referred to the coupling between F and the mode. The driving force in eq. (2) is given by

$$F\approx 2Crh\left(\frac{p_0+p_1}{2}-\frac{\rho U^2}{\sqrt{ru^3}}\right), \tag{3}$$

where C is the constant term order of unity and h is the length of the membrane. Although the model may be used successfully for voice sounds, it cannot be used for whistled or tonal sounds.

To produce a better model, Fletcher and co-workers modelled the larynx by a simple series impedance $L = j\omega\rho l/A$, where l is the length and A is the cross-sectional area of the larynx. They considered the mouth as a short tube, with a varying cross-sectional area controlled by raising and lowering of the tongue. For the beak, they assumed a conical structure and used eq. (4) below for estimating the beak impedance

$$K(f,g)=j\frac{\rho c}{A_B}\left[\frac{\csc^2(\kappa\delta/2)}{\cot(\kappa\delta/2)-\kappa\delta/2}-\cot\left(\frac{\kappa\delta}{2}\right)\right], \tag{4}$$

where $k = 2\pi f/c$, A_B is the cross-sectional area of beak base, and δ is an end correction based on measurements with a light sheet-metal beak model. It is given in terms of length of the peak l_B, frequency f and tip gape g as

$$\delta\approx 0.05l_B+10^{-5}fl_B^2/g. \tag{5}$$

Fletcher and Tarnopolsky[40] simplified the model for vocal tract of birds using two two-port elements (trachea and mouth), one single-line element (larynx), and one one-port element (beak) (Figure 2). Here, the two-port elements may be analysed using 2 × 2 impedance matrices, giving the total input impedance of the model as

$$Z_{in}=T_{11}-\frac{T_{12}^2(M_{22}+K)}{(T_{22}+M_{11}+L)(M_{22}+K)-M_{12}^2}, \tag{6}$$

where L and K are the input impedances of the larynx and beak respectively. T_{12} is the trans-impedance and T_{22} the output impedance of the trachea in two-port representation using impedance parameters. Similarly, M_{11}, M_{12} and M_{22} represent input impedance, trans-impedance and output impedance of the mouth respectively.

A one-string system to model tonal sounds was suggested by Casey and Gaunt[41]. The membrane was assumed as a vibrating string. Doya and Sejnowski[42] used both models for producing a mixture of tonal harmonic sounds and noisy components.

Studies have suggested that the sound of birds is produced by tissue folds similar to the human vocal folds[43,44]. Gardner and co-workers used two-mass model, a simplification to geometrical dimensions of the folds, assuming that the folds are controlled by bronchial pressure, giving average pressure at the tracheal side of the folds

$$p_1=p_0\left(1-\frac{u_a}{u_b}\right), \tag{7}$$

where p_0 is the driving pressure, and u_a and u_b are the displacements of the upper and lower edges of the labia respectively. The labial displacements u_a and u_b may be expanded in terms of phenomenological constant τ as

$$u_a=u_{a0}+u+\tau\frac{\mathrm{d}u}{\mathrm{d}t}, \tag{8}$$

$$u_b=u_{b0}+u-\tau\frac{\mathrm{d}u}{\mathrm{d}t}, \tag{9}$$

where u_{a0} and u_{b0} are the positions of the upper and lower edges of the labia at rest respectively. Here, u is the displacement of the membrane/labia.

The position of u can be calculated as follows[45]

$$\frac{\mathrm{d}^2u}{\mathrm{d}t^2}-(cu^2-p_0)\frac{\mathrm{d}u}{\mathrm{d}t}-ku-F=0, \tag{10}$$

where k is the restitution constant, c the dissipation constant, p_0 the driving pressure and F is a force term against the vibrating labia.

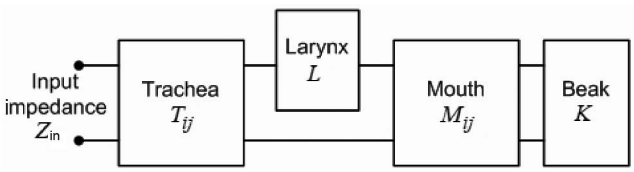

Figure 2. Model for vocal tract of birds[40].

Methodology

Several software packages are available for speech analysis, synthesis and simulation. Among these packages, COMSOL Multiphysics is more advantageous because of convenient user interface and the availability of several useful options for displaying the results. Based on overall preliminary studies, COMSOL Multiphysics was selected as the suitable simulation and modelling software[46–48]. The methodology for using COMSOL Multiphysics may be divided into the following sub-sections: geometry configuration, material and components, meshing parameters, modelling physics, and analysis plots selection (Figure 3).

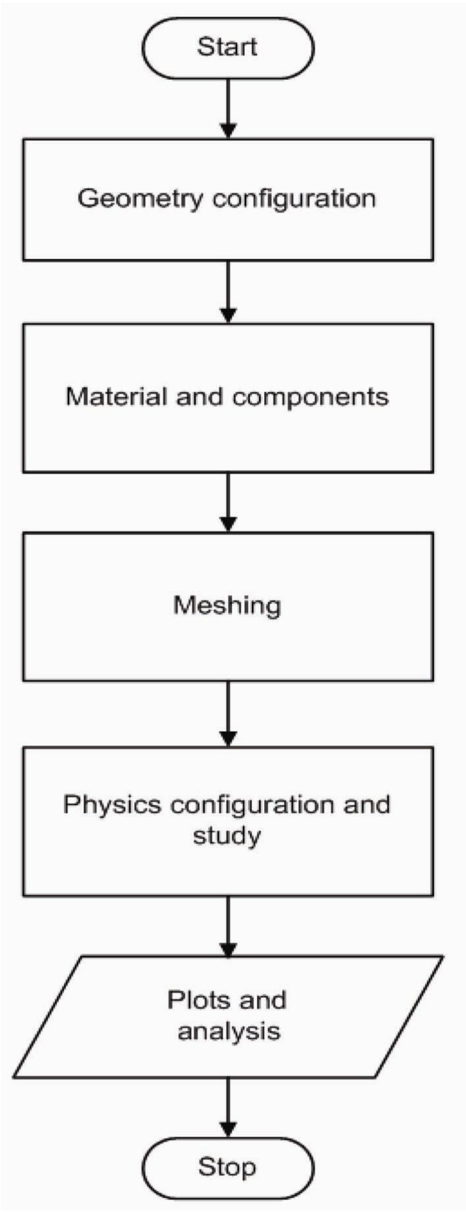

Figure 3. Methodology for vocal tract configuration of human beings and birds using COMSOL Multiphysics.

Geometry configuration selection

The vocal tract geometry for human beings, parrots and crows was set using the dimensional information available in the literature[5,6,18,19,31,33,49,50]. For human beings, the length of the vocal tract was fixed as 17 cm (refs 31, 33, 49). The vocal tract length for parrots and crows was fixed as 9 cm (refs 5, 6, 50) and 11 cm (refs 5, 18, 19) respectively. The shape of the vocal tract of parrots and crows was modified in accordance with the shape of the human vocal tract, but only varying the shape of the tongue, keeping other portion of the vocal tract intact. Figure 4 shows the shape and dimensions of the vocal tracts for the three cardinal vowels.

Material and components selection

The material of the boundary of the vocal tract was selected as tissue and interior of the vocal tract as air. The vibrations in the vocal tract were simulated using normal acceleration at the base of the vocal tract as $y_0\omega$, where y_0 is the displacement and ω is the frequency of vibration. The value of the displacement was fixed at 1 mm. The boundary of the vocal tract was taken as a hard boundary, except the outlet, i.e. mouth, which was taken as soft boundary. The pressure was measured using a point probe fixed near the mouth.

Meshing parameters selection

Mesh divides the domains into smaller units consisting of either triangular, quadrilateral, tetrahedral, hexahedral, prism, or pyramid elements. If the boundary is curved, these elements represent only an approximation of the original geometry. COMSOL Multiphysics creates a mesh that adapts to the current physics settings in the model. The selection may be modified by defining the element size. Here physics-controlled mesh with finer mesh element size has been selected.

Modelling physics

Analysis of the vocal tracts was done using the laws of acoustics. As sound is an acoustic wave generated by a disturbance in the air due to some source creating a wave of alternating high and low pressure, it obeys the laws of geometric acoustics. Sound waves in a lossless medium may be resulted as follows[48]

$$\frac{1}{\rho_0 c_s^2}\frac{\partial^2 p}{\partial t^2}+\nabla\cdot\left(-\frac{1}{\rho_0}(\nabla p-q)\right)=Q, \tag{11}$$

where p is the pressure, ρ_0 the density and c_s is the speed of sound. There are two more optional sources – dipole source q and monopole source Q.

The bulk modulus is denoted by β and mathematically expressed as

$$\beta = \rho_0 c_s^2.$$

In case of a time-harmonic wave, pressure varies with time as

$$p(x,t) = p(x)e^{i\omega t}, \tag{12}$$

where $\omega = 2\pi f$ is the angular frequency and f is the frequency (Hz). The equation for acoustic waves reduces to an inhomogeneous Helmholtz equation for the same harmonic time-dependence in the source terms

$$\nabla.\left(-\frac{1}{\rho_0}(\nabla p - q)\right) - \frac{\omega^2 p}{\rho_0 c_s^2} = Q. \tag{13}$$

After removing the source terms, eq. (13) can also be solved for eigen modes and eigen frequencies treating boundary conditions as sound-hard boundaries, sound-soft boundaries, impedance boundaries or radiating boundaries. In lossy media, an additional term of first order in the time derivative needs to be introduced to model attenuation of the sound waves

$$\frac{1}{\rho_0 c_s^2}\frac{\partial^2 p}{\partial t^2} - d_a\frac{\partial p}{\partial t} + \nabla.\left(-\frac{1}{\rho_0}(\nabla p - q)\right) = Q. \tag{14}$$

Even in lossless medium, attenuation frequently occurs by interaction with the surroundings at the boundaries of the system. For frequency domain or time-harmonic formulation, eq. (14) may be simplified as

$$\nabla.\left(-\frac{1}{\rho_c}(\nabla p - q)\right) - \frac{\omega^2 p}{\rho_c c_c^2} = Q, \tag{15}$$

where $p = p(x, \omega)$. The frequency response is computed with a parametric sweep over a frequency range using a harmonic load with this technique.

When there is damping, ρ_c and c_c are complex-valued quantities.

In 2D, pressure is of the form

$$p(r) = p(x,y)e^{-k_z z}.$$

Using this in eq. (15) gives

$$\nabla.\left(-\frac{1}{\rho_c}(\nabla p - q)\right) - \frac{1}{\rho_c}\left(\frac{\omega^2}{c_c^2} - k_z^2\right)p = Q, \tag{16}$$

where k_z, known as out-of-plane wave number, is set on the pressure acoustic page. Its value is taken as zero by default. In the mode analysis type, $-ik_z$ is used as the eigenvalue.

The behaviour of the vocal tract can be studied using both time domain or frequency domain in COMSOL Multiphysics. Here, only frequency domain behaviour of the vocal tract has been studied and reported that the output generated by the vocal tract can easily be characterized in the frequency domain. Also, the frequency of vibration was varied from 100 to 5000 Hz.

Results and discussion

Figure 4 shows the geometry used for simulating the vocal tracts for the three cardinal vowels /a/, /i/, and /u/ for human beings, parrots and crows in COMSOL Multiphysics. The shapes and dimensions of the vocal tract of human beings for the cardinal vowels were estimated from the literature[5,6,18,19,31,33,49,50]. The vocal tracts of parrots and crows were estimated assuming their capabilities to modulate their tongue to imitate human speech. Figures 5–7 show the sound pressure level (dB) at excitation frequency of 1000, 2000, 3000, 4000 and 5000 Hz, for the production of vowels /a/, /i/, and /u/ respectively. The analysis of Figures 5–7 shows that sound pressure level decreases with increase in excitation frequency in all the vocal tracts of human beings, parrots and crows for the three cardinal vowels /a/, /i/ and /u/. For the vowel /a/, sound pressure level decreases rapidly in the vocal tract of human beings compared to parrots and crows. For the vowels /i/ and /u/, decrease in sound pressure level is rapid in parrots compared to human beings and crows. For the vowel /u/, the sound pressure level in vocal tract of human beings decreases and increases alternately.

To study the frequency-dependent intensity of sound pressure for vocal tracts of human beings, parrots and crows, the differences of maximum and minimum sound pressure within the vocal tract for the three cardinal vowels /a/, /i/, and /u/ were estimated using COMSOL Multiphysics at different frequencies, i.e. from 100 to 5000 Hz. Figure 8 shows that for the vowel /a/, the amplitude of the first formant is maximum for the vocal tract of human beings compared to those parrots and crows. The amplitude of the second formant is maximum for the parrots, and approximately equal for human beings and crows. In the case of the third formant, the amplitude is maximum for parrots and similar for human beings and crows.

Analysis of the vowel /i/ shows that the amplitude of the first formant is maximum for parrots and low for crows and human beings, in that order. For the second formant, the amplitude is maximum for parrots and low for human beings and crows. In case of the third formant again parrots show maximum amplitude, whereas human beings and crows show almost similar amplitude.

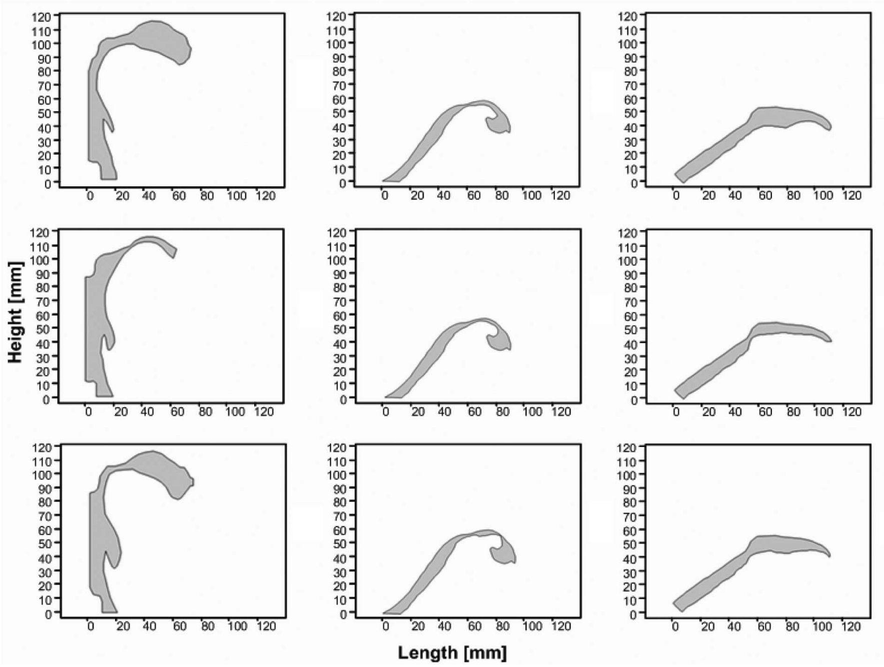

Figure 4. Geometry of the vocal tract. The first column is for human beings, the second column for parrots, and the third column is for crows. The first row is for vowel /a/, the second row for vowel /i/, and the third row is for vowel /u/.

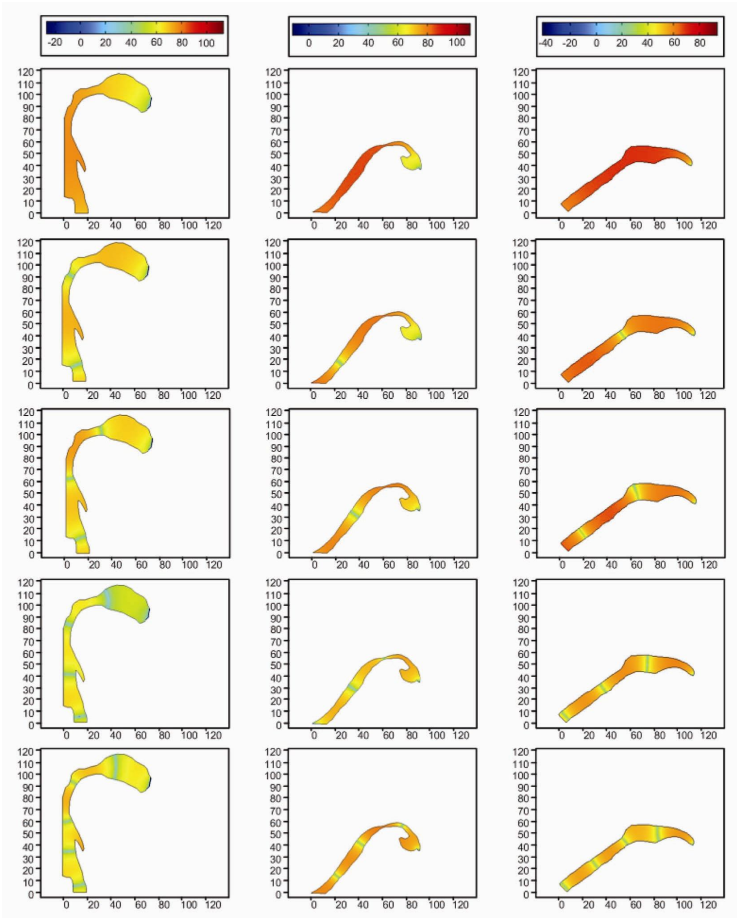

Figure 5. Surface sound pressure level (dB) for the production of vowel /a/. The first column is for human beings, the second column for parrots, and the third column is for crows. The first row represents sound pressure level (dB), the second row for frequency 1000 Hz, the third row for frequency 2000 Hz, fourth row for frequency 3000 Hz, fifth row for frequency 4000 Hz, and the sixth row for frequency 5000 Hz.

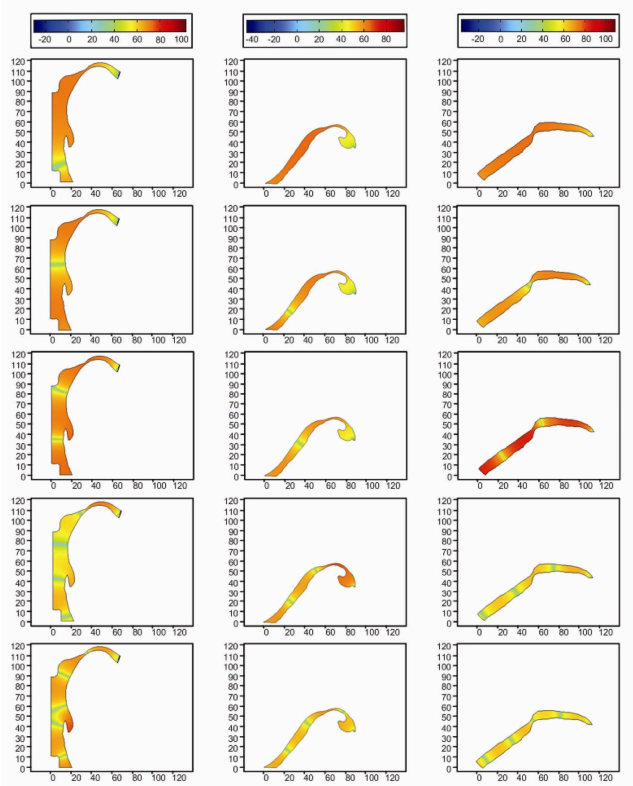

Figure 6. Surface sound pressure level (dB) for the production of vowel /i/. The first column is for human beings, the second column for parrots, and the third column is for crows. The first row represents sound pressure level (dB), the second row for frequency 1000 Hz, third row for frequency 2000 Hz, fourth row for frequency 3000 Hz, fifth row for frequency 4000 Hz, and the sixth row for frequency 5000 Hz.

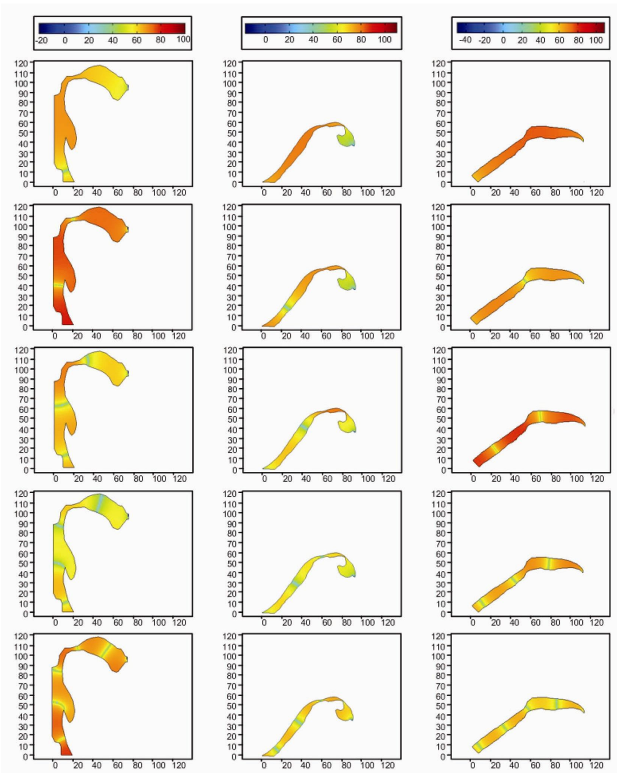

Figure 7. Surface sound pressure level (dB) for the production of vowel /u/. The first column is for human beings, the second column for parrots, and the third column is for crows. The first row represents sound pressure level (dB), the second row for frequency 1000 Hz, third row for frequency 2000 Hz, fourth row for frequency 3000 Hz, fifth row for frequency 4000 Hz and the sixth row for frequency 5000 Hz.

Table 1. Formant frequency (Hz) estimated from the vocal tract simulated using COMSOL Multiphysics for human beings, parrots and crows for the cardinal vowels /a/, /i/, and /u/

	Human			Parrot			Crow		
Vowel	F1	F2	F3	F1	F2	F3	F1	F2	F3
/a/	500	1600	2400	600	2500	3600	600	1600	3300
/i/	300	1700	2800	500	2500	3900	500	1700	3100
/u/	400	1600	2100	500	2400	3400	500	1500	3100

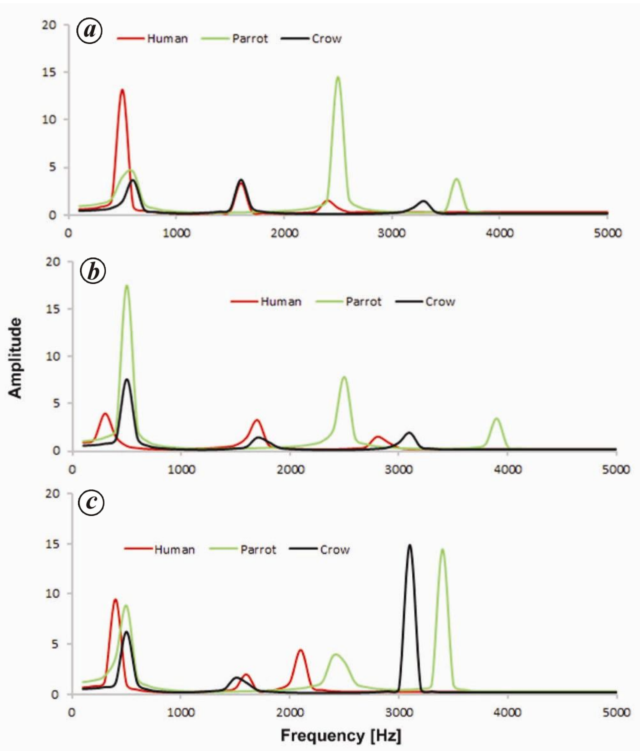

Figure 8. Differences of maximum and minimum sound pressure within the vocal tract for human beings, parrots and crows for the three cardinal vowels: (***a***) /a/, (***b***) /i/, and (***c***) /u/ at different frequencies from 100 to 5000 Hz.

Analysis of the vowel /u/ shows that the first formant has the same amplitude for human beings and parrots, but low for crows. For the second formant, the amplitude is highest for parrots and similar for human beings and crows. In case of the third formant, crows and parrots have almost the same amplitude compared to that of human beings.

The total acoustic pressure inside the vocal tract of human beings, parrots and crows was also studied for the three cardinal vowels /a/, /i/, and /u/ as the frequency response of the system (Figure 9 and Table 1). Table 1 shows the first three formant frequencies (F1, F2 and F3) estimated from the main peaks of the frequency spectra plotted in Figure 9. Figure 10 is a graphical representation of the first two formants (F1 and F2). Figures 9 and 10 and Table 1 show that parrots and crows are capable of imitating human speech, particularly vowels /a/, /i/, and /u/, if they modulate the shape of their tongue such that it corresponds to the geometry shown in Figure 4. It may also be observed from Figure 10 that acoustic space used by human beings, parrots and crows is different and non-overlapping, e.g. the acoustic space of parrots is above that of human beings, while the acoustic space of crows is on the right side of the human acoustic space. In another words, the first and second formants of parrots high compared to human beings. On the other hand, the first formant of crows is similar to that of the parrots, but the second formant is lower compared to parrots and similar to human beings. The formant scattering of human beings is maximum compared to that of parrots and crows. Specifically, the formant scattering for parrots is slightly on the lower side compared to that of crows. Informal listening tests showed that the quality of the phrases imitated by the birds was low compared to that of human beings.

Conclusions

COMSOL Multiphysics has been used for comparing the imitating capabilities of parrots and crows with those of human beings. The scope of the present study is limited to analysis of only the cardinal vowels /a/, /i/ and /u/. The shapes and dimensions of the human vocal tract for these cardinal vowels were estimated from data available in the literature. For parrots and crows, the vocal tracts were designed only by modulating the shape of their tongue. Studies were carried out in the frequency domain in the range 100 to 5000 Hz. The analysis shows that the sound pressure level decreases with increase in excitation frequency. For the vowel /a/, amplitude of the first formant is maximum for the human vocal tract. In case of vowel /i/, amplitude of the first formant is maximum for parrots. Similarly, for the vowel /u/, the first formant is of the same amplitude for human being and parrots, but low for crows. It was also observed that the acoustic space used by human beings, parrots and crows was different and non-overlapping. The formant scattering for human being was maximum and it was minimum for parrots. This study may be useful for understanding the behaviour of

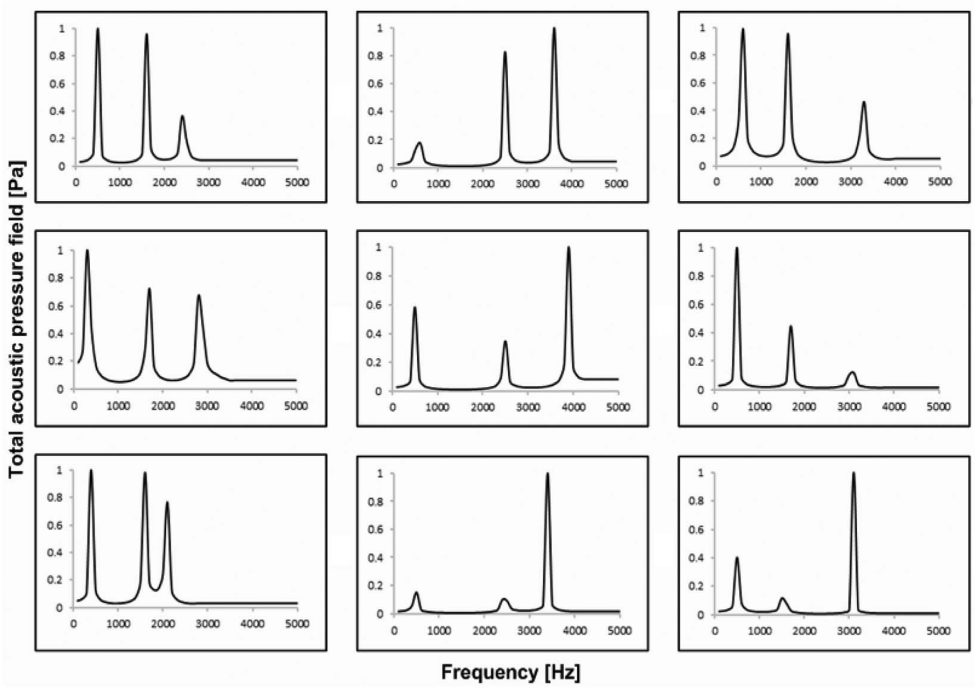

Figure 9. Total acoustic pressure field (Pa) of the vocal tract near the outlet of the mouth. The first column is for vocal tract of human beings, the second column for parrots tract, and the third column is for vocal tract of crows. The first row for vowel /a/, second row is for vowel /i/, and the third row is for vowel /u/.

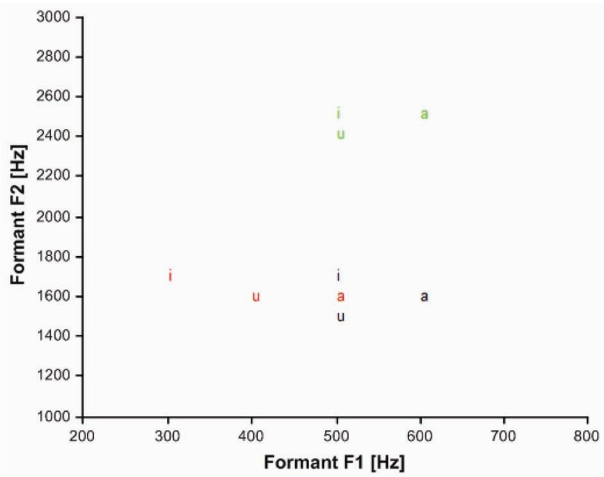

Figure 10. Scatter plot for the formants F1 and F2 for cardinal vowels /a/, /i/, and /u/ generated by the vocal tract of human beings (red), parrots (green) and crows (black) simulated using COMSOL Multiphysics.

the birds, particularly parrots and crows, in order to avoid the spread of diseases using synthesized calls for feeding medicines.

It may be noted that the present study was carried out using only the cardinal vowels /a/, /i/ and /u/. As the cardinal vowels are positioned at the edges of the acoustic region of all the vowels, the results would also be valid for other vowels falling in the acoustic region covered by these vowels.

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