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Ability of reconstituted fossil vocal tracts to produce speech Phylogenetic and ontogenetic considerations

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Abstract. We analyzed 31 skulls from now to 1.5 Ma (millions anni) BP (Before Present) for fossil hominids available at the Musée de l'Homme in Paris or in the literature: (1) 10-30 ka BP: modern humans: Paleolithic; (2) 90-200 ka BP: anatomically modern humans; (3) 45-90 ka BP: Neanderthals; (4) 1.5 Ma BP: *Homo ergaster*; These skulls are all well kept and possess a jaw in the majority of cases but the vertebral column has been reconstituted. We attempt to: (1) Localize hyoid bone and then glottis position; (2) Reconstitute a vocal tract model in a plausible way using an articulatory model; (3) Quantify the acoustic capabilities of this reconstituted vocal tract. For this purpose, we combine phylogenesis and ontogenesis. We are in a position to state that our ancestors and distant cousins were equipped with a vocal tract that could produce the same variety of vowel sounds as we can today: the vowels /i a u/. The vocal tract morphology has been favorable to the emergence and production of speech since several hundreds of thousands of years.

1. Introduction

If we suppose that our ancestors (and distant cousins) controlled their larynx and vocal tract in the same way as present-day humans, did the geometry of their vocal tract allow them to produce the universal sound structures of the languages spoken today?

From a skull with mandible and cervical vertebrae of different *hominid species*, we attempted to: (1) localize hyoid bone and then glottis position; (2) reconstitute a plausible vocal tract using an articulatory model; (3) quantify the acoustic capabilities of this reconstituted vocal tract. For this purpose, we combine phylogenesis and ontogenesis approaches. New lines of research are proposed in which orofacial abilities necessary to the emergence of speech are linked to a precursor mechanism dedicated to feeding (masticating-swallowing movements).

2. Data

We measured 31 skulls from present to 1500 kilo anni (ka) BP (Before Present) for fossil hominids available at the Musée de l'Homme in Paris or in the literature: (1) 10-30 ka BP, modern humans, Paleolithic; (2) 90-200 ka BP, anatomically modern

humans; (3) 45-90 ka BP, Neanderthals; (4) 1500 ka BP, Homo Ergaster. Almost all these skulls are well preserved and include a mandible; however, in the majority of cases the vertebral column was missing. We analyzed also the Xrays of 68 subjects longitudinally sampled from birth to adulthood provided by the American Association of Orthodontists (Barbier, 2010; Captier et al., 2010).

3. Method

The main object of the present study was to determine vocal tract contours from skull biometric data. Since this reverse relation is a one-to-many problem, constraints must be added to the estimation of extremities (lips, larynx). Note that: (1) the anterior limit of the vocal tract that corresponds to the lips. We have no information about the lips of our ancestors but the prosthion (or upper incisors) can serve as a landmark; (2) the hard palate and posterior nasal spine can be observed and used to adjust palatal vault height; (3) the mandibular plane can mark the upper limit of the hyoido-laryngeal space; (4) the anterior limit of the cervical vertebrae can be considered as the posterior limit of the pharyngeal wall space; (5) the 7th cervical vertebra is the lower limit of the hyoido-laryngeal space (Figure 1). We define two dimensions: the oral cavity width (OCW) and the pharynx height (PH); their ratio PH / WOC is referred to as Larynx Height Index (LHI), following Honda & Tiede (1998). In mammals and particularly humans, the shape of the head and the face are determined in the 15 or 20 days following fertilization. Several families of genes intervene in establishing the antero-posterior (vertical) development (HOX genes) of the embryo and in setting up the architecture of the occipital part of the head, the hyoid bone and the cervical vertebrae., the dimension and position of the hyoid bone and larynx were the same as nowadays (Figure 2).

We can hypothesize that, since the acquisition of bipedalism by our ancestors, the dimension and position of the hyoid bone, larynx and cervical vertebra are in the same range as those of modern individuals. Therefore using a variable articulatory model, we have attempted to establish a reconstitution of the fossil vocal tract within the limits defined by the incisors, the anterior part of the cervical vertebrae and the glottis. Figure 3 illustrates some results for fossils representative of different time periods.

For modern individuals we have traced vocal tract contours from Xray images corresponding to 68 subjects longitudinally sampled from birth to adulthood (on average 14 samples) provided by the American Association of Orthodontists. We determined the palatal distance from the prosthion (Pr) to the pharyngeal landmark at the level of molar plane (Ph), and the pharynx Height as the distance between Ph and Gc (glottis). Figure 4 displays one example.

4. Results

Based on the reconstitution of the vocal tracts of our collection of fossils and the measurement made on the Xrays, we have analyzed the relationship between OCW and PH. Ontogenesis of modern humans corresponds to an increase of both OCW and PH dimensions, with a larger increase for PH (inducing an increase of LHI); phylogenesis can be characterized by a stability of PH and a decrease of the OCW (increase of LHI) (Figure 5).

5. Acoustic consequences

Though the vocal tract is a 3D duct, its acoustic capabilities can be fairly reliably predicted by its sagittal 2D contours. Some parameters can be thought to have no or little influence on vocal tract acoustics: (1) palate height variability can be compensated by tongue control; (2) vocal tract curvature, in relation to head inclination, since only vocal tract length is important for low frequencies; (3) ratio between oral and pharyngeal anatomic cavities, since tongue control is however the main determinant of front and back cavities and constriction positions.

At the acoustic level, we developed a method that consists in drawing randomly n-tube tracts from all possible combinations, excluding any anatomical or articulatory constraints. The only limits on cross sectional areas A_i ($0.125 \text{ cm}^2 \leq A_i \leq 8 \text{ cm}^2$) and on section lengths L_i ($15 \text{ cm} \leq L \leq 19 \text{ cm}$) are chosen to impose an overall size similar to that of a vocal tract. The shape of the acoustic space obtained in the F1-F2 corresponds to the well known Maximal Vowel Space with the three extreme “point” or “quantal” vowels /i a u/ (Figure 6). Whatever the anatomy of oral and pharyngeal cavities, if appropriate articulatory maneuvers than can control these three parameters are physiologically possible, all hominids vocal tracts (including the Neanderthal vocal tracts) could produce speech sounds.

6. Conclusions

With the anthropometric data available for the skull and the vertebrae of fossils covering a period of 1.5 million of years, it is possible to estimate the plausible limits of vocal tracts. The typology of the *Larynx Height Index* for ontogenesis and phylogenesis shows a large range from 0.4 to 1.0. Compared to modern humans, these fossils possessed a vocal tract with a longer oral cavity and likely a similar pharyngeal height. We are in a position to state that our ancestors and distant cousins were equipped with vocal tracts that could produce the same variety of vowel sounds. However, we do not know to what extent they mastered the control skills needed to produce speech.

This capacity for control has likely been adapted, throughout the course of ontogenesis, to the dimensions of the speech production organs, thus permitting children, adolescents, and adults of either sex and age, to master sound systems that maximize the perceptual distances between their vowels.

In the domain of research on speech emergence, we are confronted with problems, constraints and limitations that are not fundamentally related to the geometry and the acoustics of the vocal tract, but rather refer to the control and learning capacities that are at the heart of the question of the emergence and structuring of language. In an exaptation process (Gould & Vrba, 1962), humans have re-used organs initially developed for breathing and feeding for the production of speech. An appealing but still very controversial hypothesis, in the line of MacNeilage, Davis (1998), Hiiemae et al. (2002), Serrurier et al. (2011) is that speech gestures may correspond to feeding activity.

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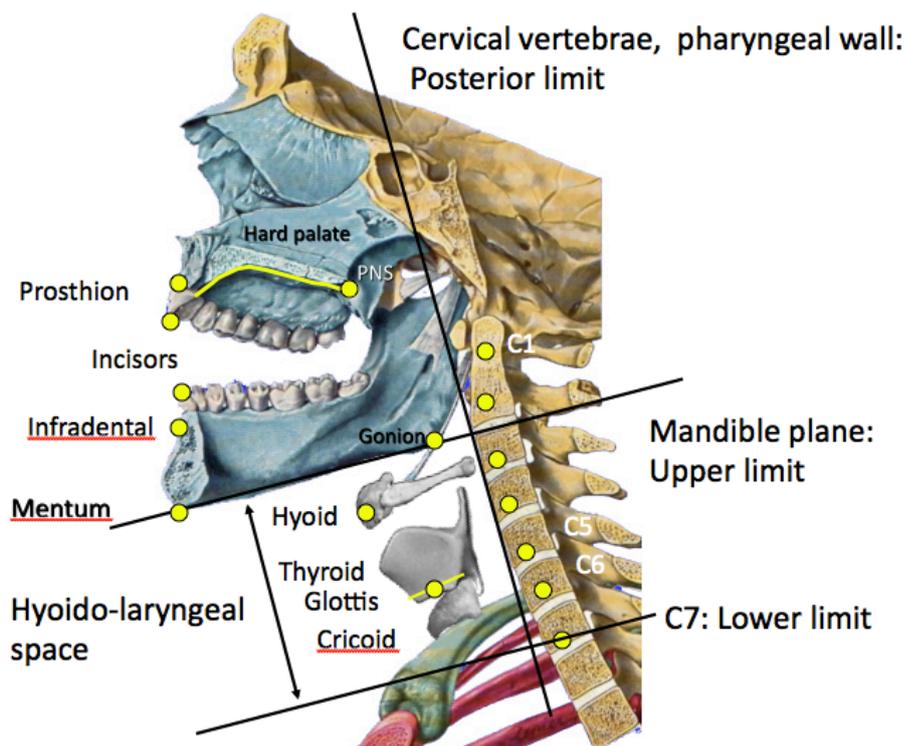


Figure 1. Bony and cartilaginous limits for soft tissues of the vocal tract.

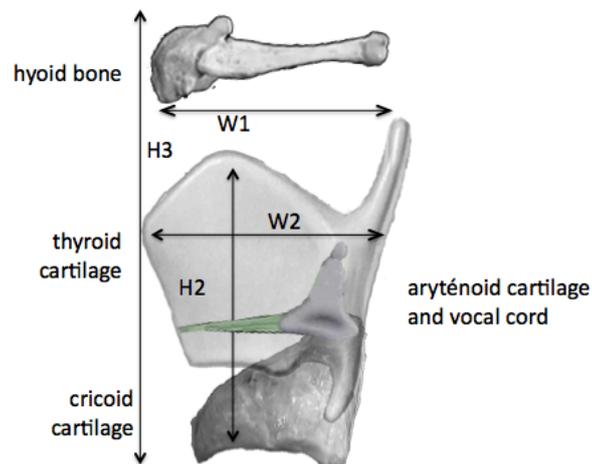
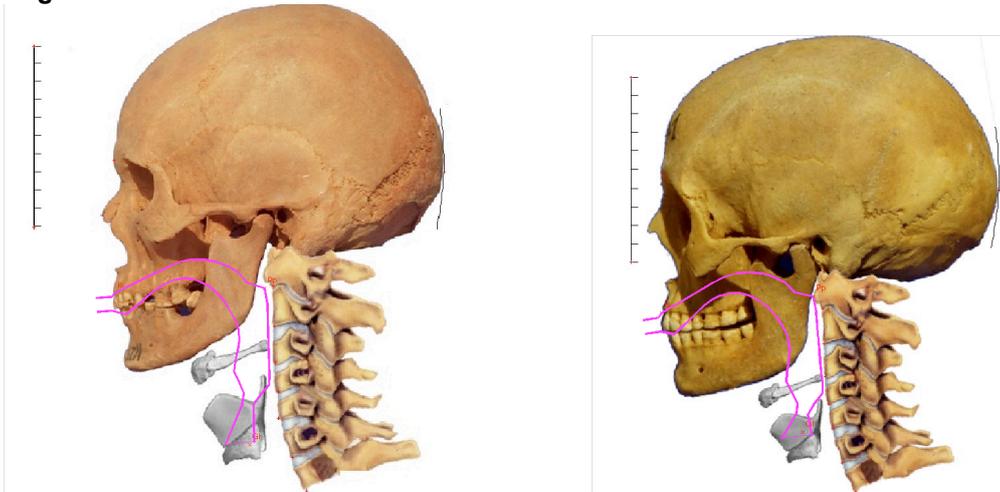


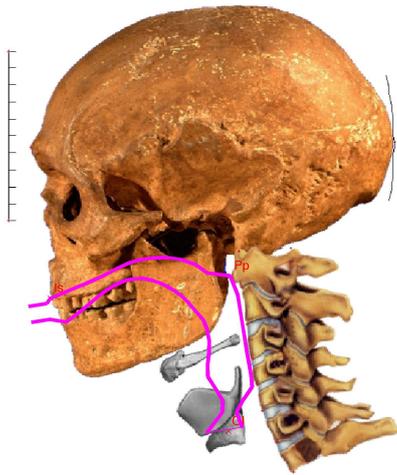
Figure 2. Mean dimensions (and standard deviations) of hyoid bone, thyroid, arytenoid and cricoid cartilages for modern men (in mm).

H3	height from lower edge of cricoid to upper edge of hyoid	63.1	(4.9)
W1	width of the hyoid bone	29.3	(5.2)
H2	main height of the larynx	38.1	(8.2)
W2	width of the thyroid	32.2	(4.3)

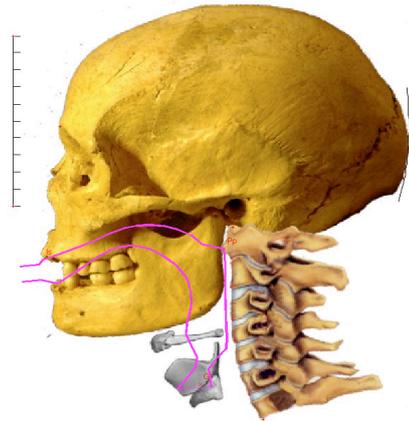
Figure 3



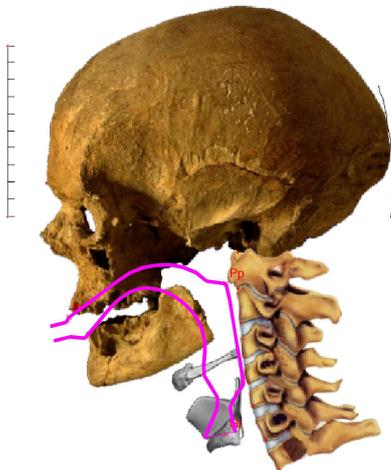
Modern man and women. For man, glottis is located between C5 and C6, and for women at the level of C5.



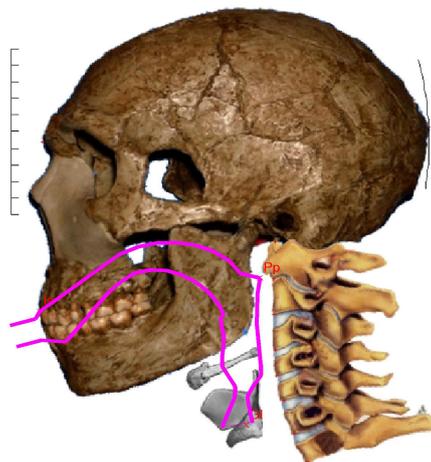
Combe Capelle (Man, 10 ka) (Homo Sapiens)



Abri Pataud (Woman, 20 ka)

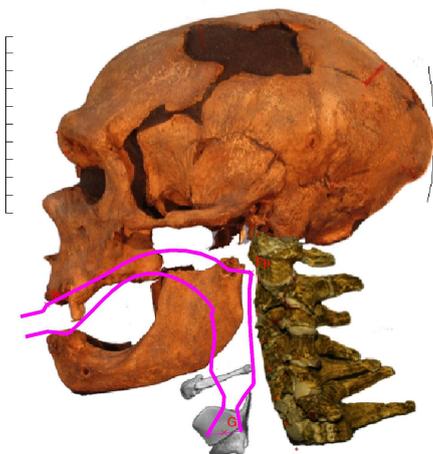


Cro-Magnon (Man, 27 ka) (Homo Sapiens)

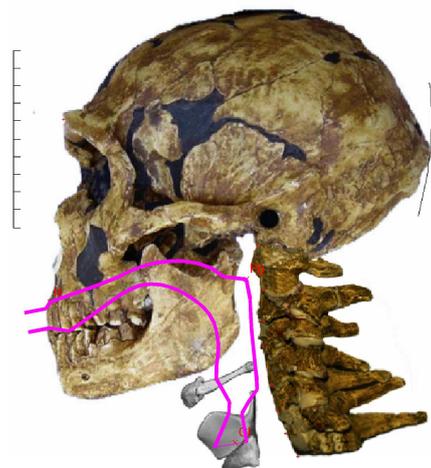


Amud (Man, 45-47 ka)

We adopted typical dimensions for vertebra. From the top of C1 to the bottom of C5 : 94 mm for men and 83 mm for women. The glottis is located at the same level as modern subjects.

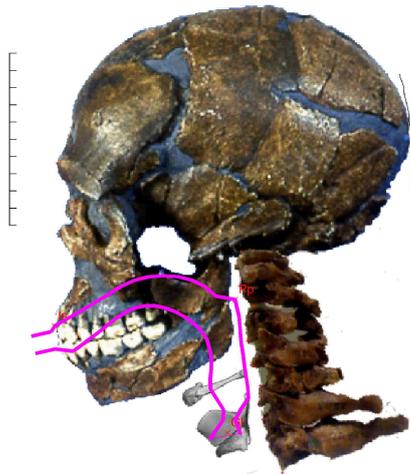


La Chapelle-aux-Saints (man, 44-60 ka)



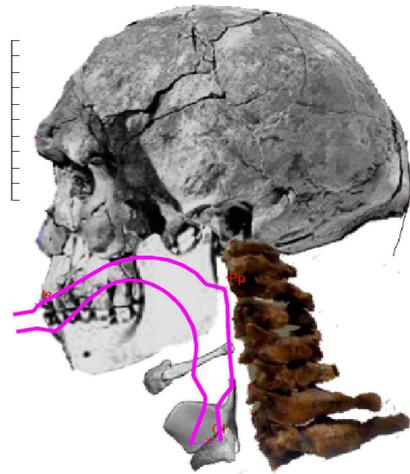
(Neanderthal) La Ferrassie (man, 72 ka).

Original vertebra. The bottom of the cricoid of Neanderthal is located between C6 and C7 (modern man between C5 and C6).



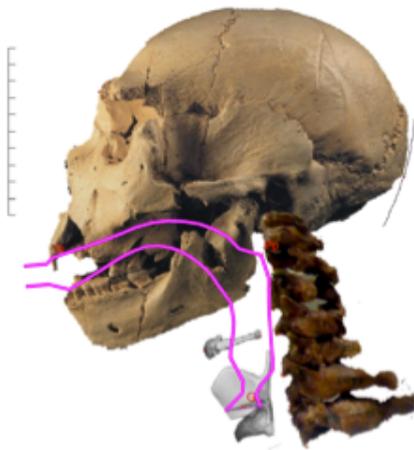
Qafzeh IX (man 90 – 100 ka)

(Anatomically modern)

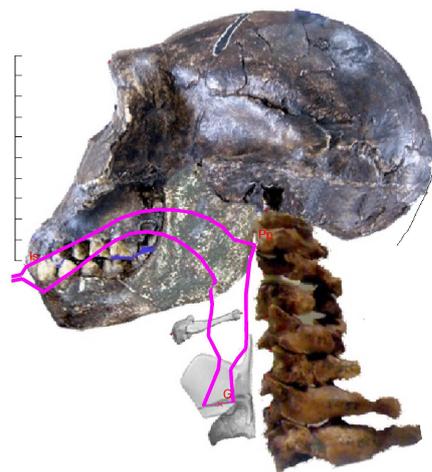


Herto (woman, 160 ka).

For these two fossils we adopted vertebra of Kebera. For the cricoid, same position as Neandertal (between C6 et C7).



Atapuerca (man, 300 ka) Pre-Neanderthal



WT 1500 (adolescent, 1.5 Ma) Homo Ergaster

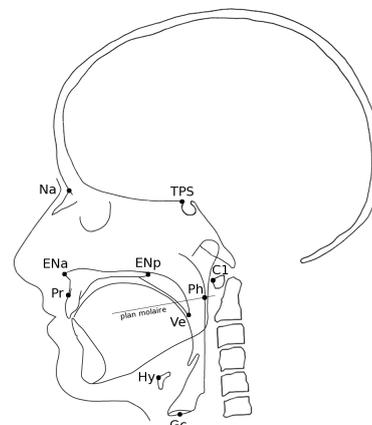
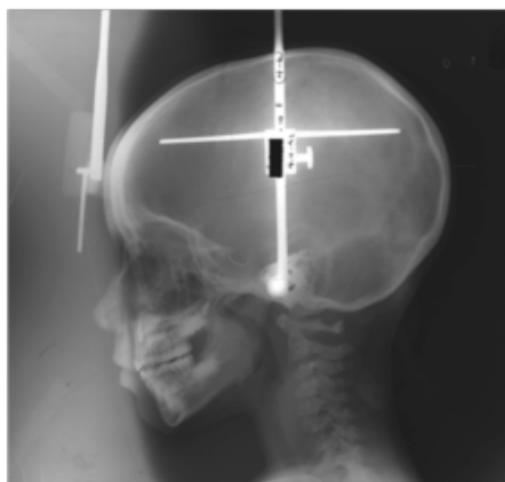


Figure 4. Illustration of the determination of vocal tract contours and landmarks. Left: original Xray image (from AAO); right: Vocal tract contours and landmarks edited manually.

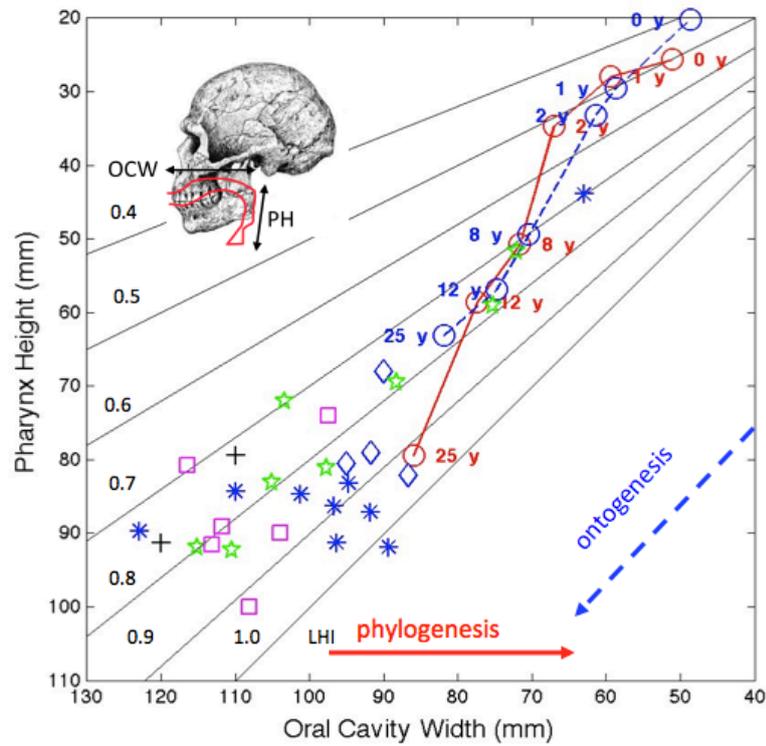


Figure 5. Measures for modern humans (males \circ , females \circ , from birth to 25 y). Fossils: sapiens, upper Palaeolithic (males $*$, females \diamond), Neanderthals (\star), anatomically modern humans (\square), Pre-Neanderthal, Atapuerca (+) and Homo Ergaster WT 15000 (+).

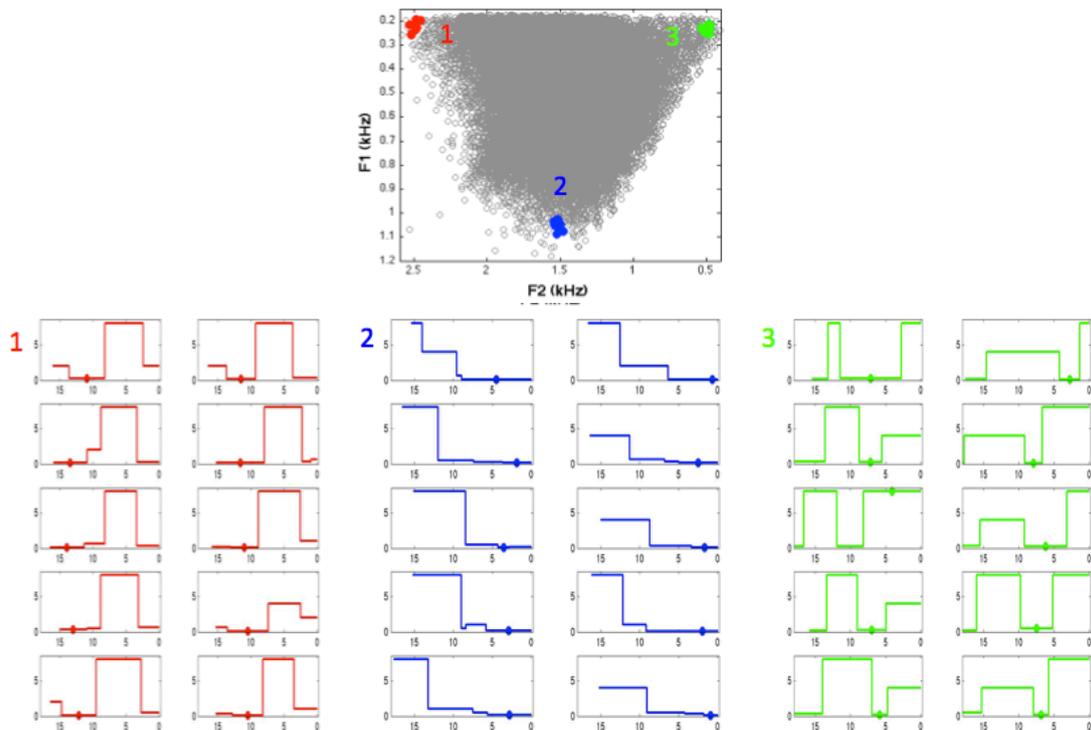


Figure 6. Maximal Acoustic Space obtained with random drawing of a 4-tube tract. At the three extremities we find configurations similar to the human /i/ a /u/.