First formant difference for /i/ and /u/: A cross-linguistic study and an explanation

Bart de Boer

Amsterdam Center for Language and Communication

University of Amsterdam

Spuistraat 210, 1012 VT Amsterdam, the Netherlands

+31 20 525 2182

b.g.deboer@uva.nl

Abstract:

The value of the first formant of high back and high front vowels (/u/ and /i/) has been determined for near minimal pairs in a 30-language sample. It is found that for 29 out of 30 languages the average of the first formant is higher for high back vowels than for high front vowels, and that for 26 out of 28 languages the majority of minimal pairs has a high back vowel with higher first formant than that of the high front vowel. A trend towards smaller differences was found in women, but this is not significant in the present data set.

Two factors may explain this observation. Firstly, the human vocal tract can only vary the position of gradual (and not abrupt) transitions of cross-sectional area. Secondly, there is a narrow tube just above the glottis (the epilarynx tube). Both factors cause the first formant of high back vowels to be raised, but neither is sufficiently important to explain the observed differences on its own.

Keywords:

vowel height; maximal vowel space; universals

1 Introduction

When the acoustic space that can be reached by a realistic articulatory model (Mermelstein, 1973) is explored systematically, an interesting asymmetry between front and back vowels is found (de Boer, 2009). It appears that the first formant[1] of the highest back vowel ([u]) is lower than the first formant of the highest front vowel ([i]). This is illustrated in figure 1A. This finding is different from the findings of Boë et al. (Boë, Perrier, Guerin, & Schwartz, 1989) who explored acoustic spaces that can be reached by different articulatory models, and who found nearly equal values for the first formants for the highest front and back vowels. The idea that the first formants of high vowels are equal is reinforced by the way in which the IPA represents vowels (illustrated in figure 1B). This representation implies a difference in the *second* formant of high front and low front vowels, but no difference is implied in the *first* formant of high front and high back vowels.

Figure 1 about here

On theoretical grounds, a lower first formant for high front vowels is also unexpected. The vowel [i] can be defined as the vowel with the highest possible second formant frequency. It can be shown that the acoustic tube that maximizes the second formant (de Boer, 2008) – given a specified length and maximal and minimal areas – has a

[1] Formants are of course only a limited representation of a vowel's acoustic properties – a more complete description would also include bandwidths and spectral tilt, among other things. However, this paper focuses on a difference between high front and high back vowels that is already measurable by only taking the first formant into account.

higher first formant than the acoustic tube that minimizes the second formant (the tubes are illustrated in figure 2B). For example, for a tube of 16 cm length, a maximal area of 8 cm^2 and a minimal area of 1 cm^2, the tube that maximizes the second formant has a first formant of 371.8 Hz (and a second formant of 2726.6 Hz) while the tube that minimizes the second formant has a first formant of 333.9 Hz (and a second formant of 709.9 Hz). When the acoustic tract can be deformed without constraints it is therefore possible to produce an [u] that has a lower second formant than that of [i]. However, this is not reflected in the model data of figure 1A.

Is the difference between front and back vowels an artifact of Mermelstein's articulatory model, or is it a real phenomenon? There is anecdotal evidence from measurements of vowel production in different languages that the first formant is higher for /u/ than for /i/. Escudero et al. (2009) find it for Brazilian and European Portuguese[2], and explicitly remark that it can also be found in other languages and that it therefore might be a "universal principle". Chao (1968, Fig. 2), when discussing the cardinal vowels of the IPA, remarks on the lower first formant of [i]. On the other hand, it is possible to find counterexamples in the literature. Hay et al. (2006) for example, present data showing that for German female speakers, the back vowels have lower F_1 than the front vowels (their figure 4b).

Understanding the exact range of articulations that can be made with the human vocal tract is important for understanding the functional pressures that shape inventories of speech sounds. The fact that high back vowels tend to have somewhat higher first formant frequencies than high front vowels might help to explain why languages tend to have fewer back vowels than front vowels if they have unequal numbers of front

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[2] When referring to vowels in languages, slashes will be used, while when referring to vowels without reference to language, square brackets will be used.

and back vowels (e. g. Schwartz, Boë, Vallée, & Abry, 1997). However, in order to establish the relation between the first formant of high front and back vowels as a universal tendency rather than as an accidental property of certain languages, a cross-linguistic study with a medium number of languages is necessary. Such a cross-linguistic study is presented in this paper.

2 Data and methods

A sample of 30 languages, inspired by Greenberg's (1963) 30-language sample was used (Table 1). The recordings were taken from the UCLA Phonetics lab archive ("the archive")[3]. As the archive does not contain all of the languages in Greenberg's proposed 30-language sample, some substitutions were made. Replacements from a similar language group and region were used, to preserve phyletic and geographic diversity. Only in the case of Songhay (written as Songhai in Greenberg's original sample) where there were not enough examples of /i/ and /u/ in the archive, it was decided to replace it with the Papuan (Torricelli) language Bukiyip, as Papua New Guinea was not represented at all in Greenberg's sample. The vowel systems of the languages were deliberately not inspected before the selection of the sample in order to avoid all bias. Two languages in Greenberg's sample (Italian and Japanese) were not available in the archive, but for these languages usable information could be found in the literature (Disner, 1983; Keating & Huffman, 1984; Ladefoged & Maddieson, 1996).

Table 1 about here

[3] http://archive.phonetics.ucla.edu/, retrieved October 2009

For each language, a list of (near) minimal pairs was selected from the available recordings. It is important to do pairwise comparisons between (near) minimal pairs, because phonetic context has an important influence on vowel formants. It is possible that this influence is larger than the systematic difference between /i/ and /u/, and doing a comparison between averages would therefore lead to an important loss of resolution. Also, vowels in the context of /w/, /j/ and nasals were avoided as far as possible because of the complications of assimilation and nasalization. Finding perfect minimal pairs was often impossible and therefore the focus was on finding near minimal pairs. Pairs of words were selected such that the places of articulation of the consonants surrounding the vowel were as similar as possible, and such that vowel length and stress were the same. None of the original recordings were made with the research question of the present paper in mind and as a result it was never possible to find very many (near) minimal pairs.

On most recordings, the same word was pronounced multiple times. As different repeats of a word tended to differ in speaking rate, only words that appeared in the same position of the sequence of repeats were compared with each other. For example the first repeat of a member of a minimal pair would only be compared with the first repeat of the other member of that minimal pair, not with the second or third repeat.

In the archive, some languages had recordings of multiple speakers. Two selection criteria were used. First, because different word lists were used for different recordings of the same language, the word list was selected from which the best set of (near) minimal pairs could be compiled. Second, recordings where the quality was not good enough were excluded. Unfortunately this lead to the exclusion of almost all recordings made on cassette tape, and therefore many recordings used in this paper are either relatively old (made on reel tape), or very recent (digital). This scarcity of data also meant that only for Yoruba, minimal pairs could be investigated for both a male and a female speaker.

Vowel formants were measured using the LPC-analysis system of PRAAT (Boersma & Weenink, 2008). Standard settings were used, except for the ceiling, which was taken to be 5500 . The formants were measured for the part of the vowel were acoustic energy was maximal, if the first formant was not changing rapidly at that point due to co-articulation. In the cases where the first formant did change rapidly, the center of the steadiest part of the vowel was measured.

3 Results

The measured formant values for the highest front and highest back vowels of each language are given in table 2. This table contains two measures of the relation between F_1 of /u/ and /i/. These are the fraction of minimal pairs were the F_1 of /u/ is higher than that of /i/ and the average difference between F_1 of /u/ and /i/. The first measure is the ratio between the values of columns "Cm" and "u>i" and the second is found in the column "ΔF_1". Because the data of Italian and Japanese were not derived from direct comparisons of minimal pairs, the first measure cannot be calculated for these two languages.

Table 2 about here

Because of the small number of minimal pairs per language, in many languages in the sample no significant difference between /i/ and /u/ is found when testing with data from only that language. In a sample of many languages, this problem can be avoided by considering, for each language in the sample, the *direction* of the difference between /i/ and /u/ as a data point. The first measure can be determined for 28 languages. For 26 of these, the majority of (near) minimal pairs has /u/ with higher F_1 than /i/. According to the sign test the null hypothesis that F_1 is equal for /i/ and /u/ across languages can be rejected with $P = 4.2\times10^{-7}$. The second measure can be determined for all languages in the sample. For 29 of these the average of F_1 for /u/ is higher than for /i/. According to the sign test, the null hypothesis can again be rejected, with $P = 5.8\times10^{-8}$. The sign test was used because it is a parameter-free test and because it is very conservative (for reference, the second measure can also be tested with a t-test, and then gives $P = 2.32\times10^{-8}$ for $t(30) = 7.50$). An idea of the effect size can be obtained by calculating Cohen's *d*, which is equal to 1.47 (excluding Italian for which no standard deviation of the formant values was known).

For the first measure, Hawaiian and Turkish are counterexamples. Whereas in Hawaiian exactly half of the minimal pairs have F_1 of /u/ higher than that of /i/, in Turkish the majority of minimal pairs has /i/ with higher F_1 than /u/. As for the difference in average F_1, in Hawaiian the difference is in the right direction (albeit only 1 Hz, and therefore not significant) but in Turkish the average of F_1 for /i/ is higher than that for /u/. There is one other language (Kannada) where the average difference in F_1 is smaller than 10 Hz. Also, in most languages there are (near) minimal pairs were /u/ has lower F_1 than /i/. The tendency that /u/ has higher F_1 than /i/ is therefore not a true universal but a *universal tendency*.

The data of the three languages with very small differences between /u/ and /i/ are all from female speakers. This raises the question of whether female speakers have a less pronounced tendency for producing higher F_1 in /u/ than in /i/. There are 11 languages for which there is data of female speakers. Of these, 9 have more minimal pairs with higher F_1 for /u/, 1 has equal numbers of minimal pairs, and 1 has fewer minimal pairs. According to the sign test, the null hypothesis that F_1 is equal for /u/ and /i/ can be rejected with *P* = 0.021. There are 10 languages for which the average F_1 for /u/ is higher than that for /i/, and on the basis of this measure, the null hypothesis can be rejected with *P* = 0.012. It therefore appears that for women, too, the F_1 of /u/ tends to be higher than that of /i/. The median of the difference in F_1 for men is 50 Hz, and for women it is 27 Hz. Testing with the Wilcoxon rank sum test for the null hypothesis that the distributions have equal median, it is found that *P* = 0.16, and therefore it cannot be concluded that they are different (but it should be stressed that this does not mean that they are not different, just that given the data, the difference cannot be detected.)

There is no statistically significant correlation between the number of vowels in a language and the distance in the first formant between /u/ and /i/. Pearson's correlation coefficient *r* (calculated with exclusion of the Yoruba female data in order to prevent duplication of the Yoruba data point) is 0.0233 and for this data set that corresponds to *P* = 0.85. The null hypothesis that there is no correlation can therefore not be rejected.

4 Conclusion and discussion

The data from the cross-linguistic sample show that there is a strong tendency for languages to have a higher first formant for /u/ than for /i/. Although there is an indication that in female speakers this effect is less strong than in male speakers, for the data set investigated here, this effect was not statistically significant (but the expectation is that it would be significant in a larger data set).

There appears to be a continuous range of differences between the first formant frequency of the high back vowel and the high front vowel. This falsifies the hypothesis that there are multiple clearly distinguishable types of languages in the sample: one type with /i/ and /u/, one type with /i/ and /o/ and one with /i/ and /ɯ/ etc. There also appears to be no correlation between the number of vowels in a language's vowel system and the difference between /i/ and /u/. It really appears to be the case that the high back vowel usually just has a higher first formant than the high front vowel.

There is one exception in the data set investigated here: Turkish as pronounced by a female speaker. There are also a number of languages with a very small difference between /i/ and /u/, such as Hawaiian and Kannada, both also pronounced by female speakers. The phenomenon therefore does not appear to be exceptionless, but just a very strong tendency. It is tempting to speculate that the exceptional status of Turkish has to do with the fact that it has both a high front rounded vowel /y/ and a high back unrounded vowel /ɯ/ in addition to the usual high front unrounded and high back rounded vowels. However, the two other languages with very small differences have ordinary five-vowel systems, while Korean, which does have a high mid unrounded vowel (transcribed /ɨ/) and is also represented by a female speaker has an average difference between /u/ and /i/. As far as the current data set is concerned, the difference between /i/ and /u/ cannot be predicted on the basis of the vowel system.

What could then be the explanation of the difference? This paper proposes an anatomical/acoustical explanation. Given the anatomy of the vocal tract and its articulatory constraints, high front vowels can be articulated with a lower first formant than high back vowels. This phenomenon was illustrated in figure 1A for the male vocal anatomy, and is illustrated in figure 2A for the female vocal anatomy (de Boer, 2009). For reference the male acoustic space is repeated in this figure, and it can be observed that the female anatomy allows for a somewhat smaller difference in first formant between high front and high back vowels.

Figure 2 about here

However, the observation based on these models is not yet an explanation. What causes the possibility to articulate high front vowels with lower first formants? A purely behavioral explanation in terms of articulatory undershoot is unlikely, as the language sample was based on (near) minimal pairs to control for just such an effect, while the realistic articulatory model (in which every articulation has equal probability) shows exactly the same tendencies.

The explanation for the difference between human /i/ and /u/ is therefore more likely be related to constraints on articulation. One notable difference between the tracts with minimal second formant and maximal second formant is that the minimizing tract has abrupt transitions in the cross-sectional area, while the maximizing tract has gradual transitions. Because the human vocal tract consists of soft, continuous tissue it is only possible to vary the position of gradual transitions (there are abrupt transitions, but these have a fixed position). Therefore the tract that maximizes the second formant can in principle be approximated better with a real vocal tract than the tract that minimizes the second formant. A tract that minimizes the second formant, but that has gradual transitions like the maximizing tract would look like the third tube from above in figure 2B. It turns out that, ignoring radiation and damping, this tract has exactly the same first formant as the tract that maximizes the second formant (because of the symmetry of the tracts). Although the impossibility to make abrupt transitions of cross sectional area does decrease the difference in first formants, it does not explain why the first formant of /u/ tends to be *higher* than that of /i/in human languages.

A potential feature that can explain this extra difference is the epilarynx tube. It is the part of the vocal tract just above the vocal folds that still lies inside the larynx. It has relatively constant cross-sectional area. Story et al.'s measurements (1996; 1998) show that the epilarynx tube has a cross-sectional area of 0.5–1 cm^2. Adding such a tube (1 cm^2 area and a length of 1.6 cm – approximately the length of the epilarynx tube in Story et al's (1998) measurements of the female vocal tract) to the tube for [u] with gradual transitions (illustrated as the bottom tract in figure 2B) results in a first formant frequency of 398.9 Hz. The tube that maximizes the second formant frequency (the i-tube) already has a narrow tube in the right place, and does not need to be modified to incorporate the epilarynx tube. The difference between the first formant of the original i-tube (371.8 Hz) and the modified u-tube (398.9 Hz) is within the range of the experimental findings. Attaching an epilarynx tube to an u-tube with sharp transitions results in a first formant of 359.2 Hz, so it appears that given the constraints on the dimensions of the human epilarynx tube, both gradual transitions and the epilarynx tube are needed to explain the higher first formant of [u] compared to [i]. This observation can be interpreted in terms of undershoot: as it is more difficult to approximate an ideal [u] than to approximate an ideal [i], then given a level of articulatory accuracy, [u] will always appear to be produced with more articulatory undershoot than [i].

It is interesting to note that given Story et al.'s (Story, et al., 1996, 1998) observations, the human male vocal tract has a much more prominent epilarynx tube than the human female vocal tract. It is tempting to speculate that the potential difference between male and female speakers in the data presented here might be explained by this anatomical difference. However, in order to investigate this, anatomical and articulatory data from individual speakers is needed.

The findings presented in this paper illustrate the possibility to explain cross-linguistic observations (and perhaps individual differences) from anatomical and acoustic analysis. They also reinforce the observation that there is more acoustic room at the front of the vowel space, which would explain why languages tend to have more front vowels than back vowels (Crothers, 1978; Maddieson, 1984). It is likely that the combination of articulatory modeling, cross-linguistic analysis of speech sounds and acoustic and anatomical analysis can help explain more phonetic universals. These universals do not have to be of vowel systems, but could equally well be of other aspects of speech, or focus on different acoustic properties. With the availability of on-line recordings of large numbers of languages such work is now within reach of researchers worldwide.

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Figure 1: Panel A: Acoustic range derived from an articulatory model of the male vocal tract. Panel B: classical perception of vowel space as illustrated by the standard IPA representation. The data in panel A are based on 100 000 random articulations of Mermelstein's (1973) articulatory model, using a re-implementation described in de Boer (2009). Note that the high back vowel has lower F_1 than the high front vowel in the model data.

Figure 2: Panel A: Female acoustic range compared to male acoustic range. Note that the top of the female acoustic range falls less steeply for lower second formant frequencies. Panel B: tracts for minimal and maximal F_2, given that maximal area is 8 times minimal area. Note the gradual transitions for the maximal formant, and the abrupt transitions for the minimal formant. Also shown are realizations of [u] with gradual transitions as well as [u] with gradual transitions and an epilarynx tube.

Table 1: Details of language sample. "Code" is the ISO 639-3 code, "Vwl" is the number of vowels in the language, the file numbers are from the UCLA Phonetics Lab Archive, "Prs" indicates the number of (near) minimal pairs, "Cm" the number of paired comparisons.

Language	**Code**	**Greenberg**	**Vwl**	**File numbers**	**Sex**	**Prs**	**Cm**
!Xoo	NMN	Nubian	5	0000_01–0000_04	♂	4	12
Banawa	BNH	Chibcha	4	1995_01–1995_03	♂	4	8
Basque	EUS		5	1973_01–1973_04	♂	5	5
Berber	TZM		3	1973_01	♂	5	10
Bukiyip	APE	Songhai	11	1984_01	♂	2	4
Burmese	MYA		8	1983_01	♂	3	6
Finnish	FIN		8	1990_01	♀	5	10
Fulfulde (Maasina)	FFM	Fulani	5	1962_01	♂	3	3
Greek	ELL		5	1980_01–1980_03	♀	3	6
Guarani	GUG		6	1994_01	♂	3	3
Hawaiian	HAW	Maori	5	1973_01	♀	4	10
Hebrew	HEB		5	1982_01	♂	5	10
Hindi	HIN		11	1979_01	♀	4	4
Italian	ITA		7	—	♂	—	—
Japanese	JPN		5	—	♂	—	—
Kannada	KAN		5	1983_01	♀	5	10
Korean (Cheju)	KOR	Burushaski	10	1998_60	♀	2	4
Luo	LUO	Masai	9	1971_01	♀	3	3
Malay (Pattani)	MFA		6	1985_01–1985_02	♂	5	10
Norwegian (Bokmål)	NOB		14	1984_01	♂	2	6
Pitjantjatjara	PJT	Loritja	3	1976_01	♂	3	3
Q'eq'chi	KEK	Maya	5	1978_02	♂	5	6
Quechua	QUH		5	1985_01–1985_02	♂	6	8
Serbian	SRP		5	1976_01	♀	3	6
Swahili	SWH		5	1973_08–1973_09	♀	3	6
Thai	THA		9	1984_01	♂	4	8
Turkish	TUR		8	1974_01–1974_02	♀	4	5
Welsh	CYM		11	1972_01–1972_02	♂	6	12
Yoruba ♀	YOR		7	1983_01	♀	2	2
Yoruba ♂	YOR		7	1962_01	♂	3	6
Zapotec	ZPK		6–7	1987_01	♂	3	5

Table 2: Measurements of the 30 languages in the sample. Column "Cm" contains the number of near minimal pairs compared, "u>i" the number of times the first formant of /u/ was higher than that of /i/, "F_1 i" and "F_1 u" the average first formants of /u/ and /i/, respectively. Columns "σ u" and "σ i" contain the standard deviations of the first formants of u and i, respectively and "ΔF_1" the average difference between F_1 of u and F_1 of i.

Language	**Code**	**Cm**	**u>i**	**F_1 u**	**F_1 i**	**σ u**	**σ i**	**ΔF_1**
!Xoo	NMN	12	11	312	302	13	21	52
Banawa	BNH	8	8	383	307	30	12	76
Basque	EUS	5	5	369	322	19	17	47
Berber	TZM	10	9	426	351	53	29	75
Bukiyip	APE	4	4	356	304	25	17	52
Burmese	MYA	6	4	395	322	35	25	10
Finnish	FIN	10	9	435	397	40	31	38
Fulfulde (Maasina)	FFM	3	3	338	327	25	20	11
Greek	ELL	6	4	411	401	14	15	10
Guarani	GUG	3	3	437	333	16	21	104
Hawaiian	HAW	10	5	427	426	54	33	1
Hebrew	HEB	10	7	382	361	18	30	21
Hindi	HIN	4	3	350	258	73	13	92
Italian	ITA	—	—	366	315	32	28	34
Japanese	JPN	—	—	336	302	0	0	54
Kannada	KAN	10	6	413	359	47	44	3
Korean (Cheju)	KOR	4	3	399	347	22	18	62
Luo	LUO	3	3	456	394	58	26	117
Malay (Pattani)	MFA	10	10	400	283	22	25	73
Norwegian (Bokmål)	NOB	6	6	384	327	17	27	57
Pitjantjatjara	PJT	3	2	382	335	40	67	47
Q'eq'chi	KEK	6	6	380	377	52	69	52
Quechua	QUH	8	6	307	294	16	21	13
Serbian	SRP	6	4	394	382	19	27	12
Swahili	SWH	6	5	338	306	38	33	32
Thai	THA	8	7	466	418	32	48	48
Turkish	TUR	5	1	385	395	13	39	–10
Welsh	CYM	12	7	353	340	18	20	13
Yoruba ♀	YOR	2	2	340	313	7	11	27
Yoruba ♂	YOR	6	5	294	226	64	31	68
Zapotec	ZPK	5	3	324	301	15	24	23

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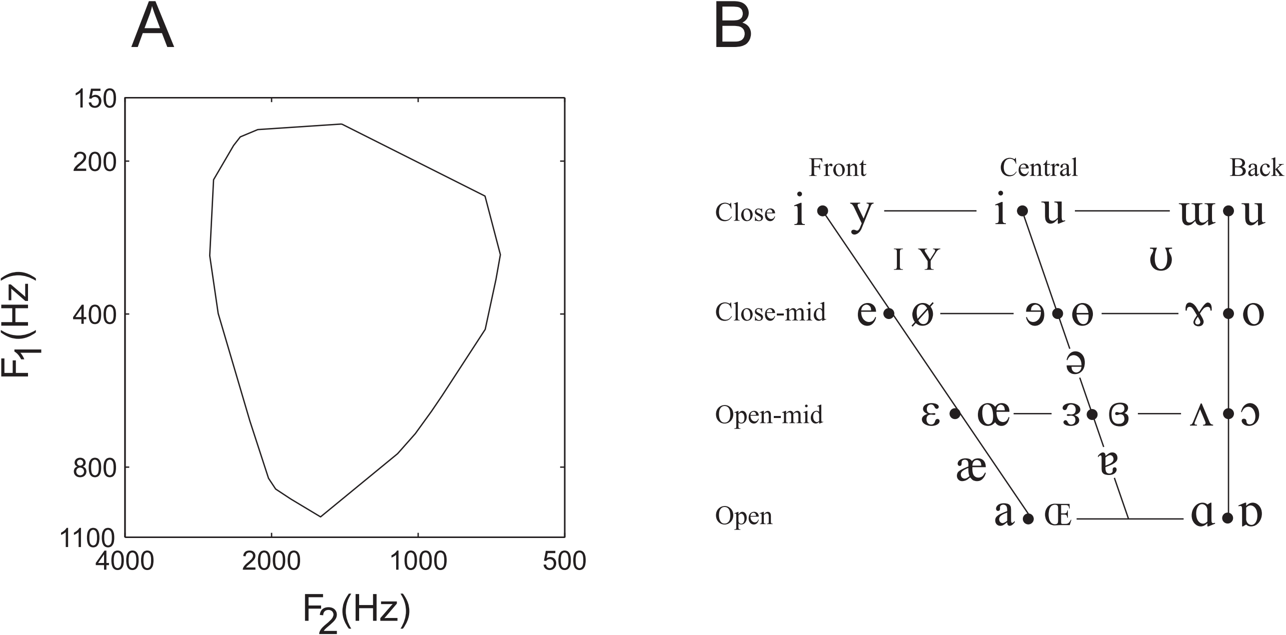
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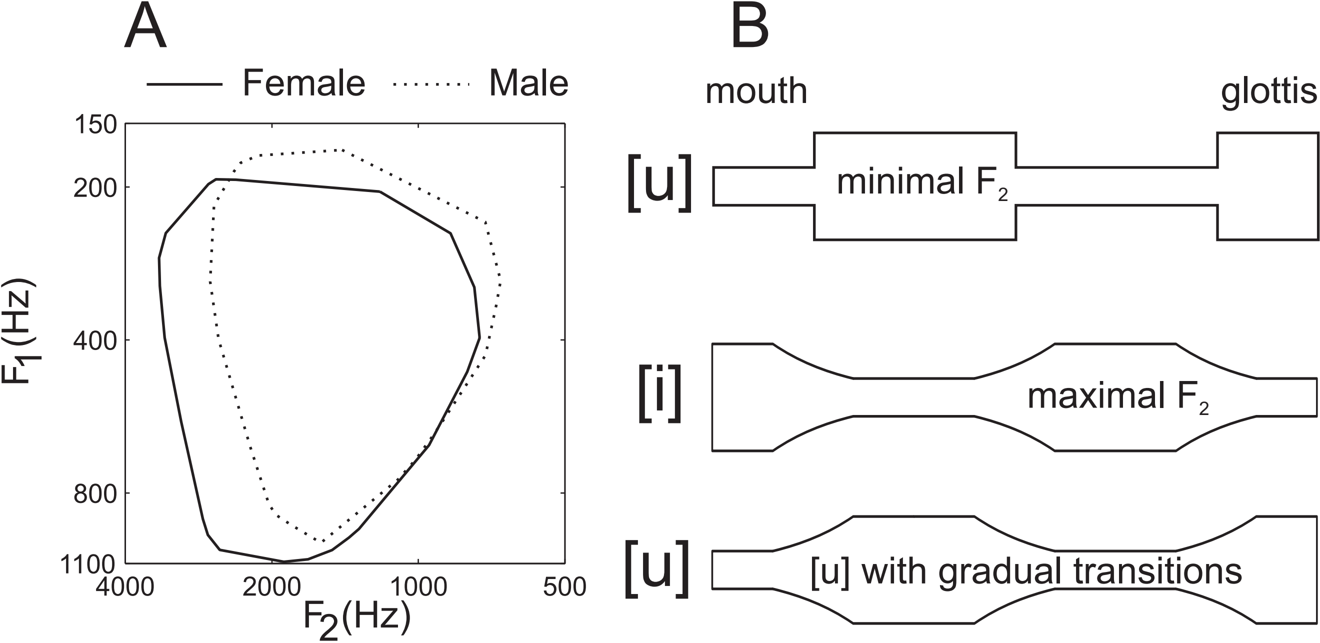
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