V-to-C Coarticulation Effects in Non-native Speakers of English and Russian: A Locus-equation Analysis*

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<Abstract>

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Locus equation scatterplots for [bilabial stop + vowel] syllables were obtained from 16 non-native speakers of English and Russian. The results indicated that both Russian speakers of English and English speakers of Russian exhibited modifications towards respective L2 norms in slopes and y-intercepts. All non-native locus equations generated exhibited linearity. Accordingly, the basic results reported in [17] were reverified by securing a larger subject base. More experienced speakers displayed better approximations to L2 norms than less experienced speakers, indicating the necessity of perception- and articulation-related learning for allophonic variations due to adjacent phonetic environments.

* Keywords: V-to-C coarticulation effects, Locus equations, F2 onsets, Vowel F2s, Bilabial stops, Non-native speakers, Foreign-language experience.

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1. Introduction

Theories of language acquisition within standard formal phonology focus mainly on contrasting patterns of sounds and disregard the role of sub-phonemic details (e.g., [1]). Many experimental results, however, have demonstrated that sound acquisition is sensitive to changes at the sub-phonemic or phonetic level. Among others, [2] and [3] for data from first-language (L1) acquisition, and [4], [5], [6], [7], and [8] for data from second-language (L2) acquisition show that phonetic details need to be independently learned. For example, [2] reported that, in CV syllables [ki] and [ka], adults showed robust coarticulatory differences between the velar stops preceding front and back vowels, but data obtained from children were more variable and did not always present the coarticulatory differences.

This study aims to provide further support for the importance of acquisition at the sub-phonemic level by means of investigating V-to-C coarticulation effects in non-native speakers in which consonants in CV syllables show systematic variations due to adjacent vowels. In this study, locus equation metrics are used to quantitatively estimate the V-to-C coarticulation effects. First, differences in the locus-equation parameters across languages will be verified, and second, phenomenon appearing in the process of their L2 acquisition will be examined.

1.1. Locus equations

Locus equations are derived from regression lines indicating that the second-formant (F2) frequencies of consonants in CV syllables vary in a highly linear fashion to contextual vowel F2's. The consonants are generally stops, and all monophthongal vowels in a language are used as contexts. Locus equations are derived by the following procedure: (1) Measurement of consonant F2's or F2 onsets ($F2_C$, taken at the first glottal pulse) and vowel F2's ($F2_V$, taken at the steady state) in all CV syllables considered, (2) plotting of all data points on x-axis for $F2_V$'s and y-axis for $F2_C$'s, and (3) derivation of straight-line regression fit of the data points. The locus equations derived are in the form of $F2_C = k*F2_V + c$ (k = slope, c = y-intercept), which was originally found by [9] (also in [10], [11], [12], [13], [14], [15], and [16]).

[11] shows an interpretation of the locus equation slopes as quantifying the extent of consonant coarticulation in vowel contexts. The slopes generally have values between 0 to 1. An idealized slope of "0" means that the $F2_C$'s do not vary despite changes in vowel contexts, and at the other extreme an idealized slope of "1" means

that the $F2_C$'s have identical values with contextual vowel F2's, and therefore, a maximal degree of anticipatory coarticulation. Usually, stops have slopes in between.

[13] shows the results of a more extensive experiment regarding locus equations produced by ten male and ten female speakers of American English. C_1VC_2 syllables (C_1 = /b, d, g/, V = /i, ɪ, eɪ, ɛ, æ, ɑ, oʊ, ʌ, ɔ, u/, C_2 = /t/) were produced in a carrier phrase. Results showed that differences in slopes due to stop places were statistically significant. Alveolar stops showed the shallowest slopes, indicating that the degree of anticipatory coarticulation is smallest, while the slopes of bilabial stops were the steepest, indicating that the amount of coarticulation is the largest. The slopes of velar stops were in between those of the alveolar and bilabial stops, but displayed large allophonic differences, i.e., maximal coarticulation in back vowel contexts and minimal coarticulation in front vowel contexts. The locus-equation y-intercepts also systematically varied as a function of stop places, and stop place comparisons across y-intercepts within language turned out to reach levels of statistical significance ([13], [14], and [15]).

1.2. Locus equations in child speech

[14] investigated locus equations produced by 3, 4, and 5-year old children. Three stop places were considered and the contextual vowels were /i, ɪ, æ, a, ʌ, u/. Regression fits of scatterplots of $F2_C$'s and $F2_V$'s in the children's speech were quite linear as did those in adults' speech. For 48 locus equations produced, R^2 values in most cases exceeded 0.90.

Group mean values of the slopes in children appeared to be analogous to those in adults; bilabial stops with the steepest slopes, alveolar stops with the shallowest, and velar stops with intermediate values. However, contrastive distinctiveness among the stop categories appeared more clearly in adults than in children. In the children's speech, distinctions between bilabial and alveolar stops and between alveolar and velar stops were clear, but distinctions between bilabial and velar stops were not significant. The insufficient distinctions between the stop categories were interpreted to be due to children's articulatory immaturity. This indicates that one attribute of articulatory maturation is to achieve the adults' norm of "a balance between coarticulatory adjustments and contrastive distinctiveness [14: p. 769]".

1.3. Aim of the study

This study aims to investigate the locus equations of non-native speakers in order to see whether the locus equations can capture developmental processes of proper CV coarticulation due to foreign-language experience. In particular, the locus equations of English and Russian bilabial stops are examined. The primary aim is to validate the experimental results reported in [17] by securing a larger subject base and analyzing the results more multilaterally.

Russian is known for its complex consonant system with almost completely systematic oppositions of palatalized and non-palatalized (or plain) consonants (e.g., [brat'] 'to take' vs. [brat] 'brother', [18]). Due to this richness of the consonant system, excessive coarticulatory effects of consonants with contextual vowels may result in insufficient distinctions with other consonants. Consonants in English, however, are allowed to have a larger degree of coarticulation with contextual vowels, because in English there is a smaller emphasis on maintaining contrasts among consonants. It can then be expected that Russian, in which consonants are least influenced by vowels, will display smaller locus equation slopes than English, in which vowels can have greater effects on consonant articulation.

Research questions to be explored are (1) whether foreign-language speakers approximate L2 norms in locus equation parameters, (2) whether the degrees of approximation to the L2 norms are explicable in terms of the extent of learners' foreign-language experience, and (3) whether L2 locus equations display linearity as extreme as L1 locus equations.

2. Methods

2.1. Subjects

Sixteen speakers participated in this experiment. Among them, native Russian speakers were nine (Group R, five females and four males, mean age 24.4, range 19-28), and native English speakers were seven (Group E, four females and three males, mean age 24.7, range 19-29). Subjects were all undergraduate or graduate students at Stanford University in the U.S. It would have been ideal to recruit subjects who do not speak any foreign languages for the native speaker groups, but it was not possible to find any native Russian speakers who do not speak English at more than advanced levels from the pool of university students residing in the U.S. All speakers in Group R participated also in a non-native experiment as Group RE (native Russian speakers of English). Native English subjects who speak Russian were also selected to serve as Group E and Group ER (native English speakers of Russian). Due to the difficulty of finding native Russian speakers and English learners of Russian from the pool of students at a university in the U.S., it was not possible to secure a larger number of subjects as planned. Subjects who spoke any foreign languages other than English for Group RE and Russian for Group ER at more than advanced levels were excluded from the subject of the experiment.

<Table 1> lists subject information. Subject numbers reflect the degree of experience with their non-native language from the most experienced (number 1) ascending to the least. The need to consider multiple determinant factors made it difficult to order the subjects by exact foreign language experience, but rough sequencing was made for the purpose of discussing the experience effects. Males and females were ordered separately.

<Table 1> Subject information

Speaker-sex-number (initial)	Age at the time of recording	Length of stay in the U.S.	Age when s/he started to learn English	Frequency of speaking English with natives	Self-evaluation of English pronunciation
R(E)M1 (AI)	25	13 years	10	daily	slight accent
R(E)M2 (LB)	27	12 years	4	daily	slight accent
R(E)M3 (DL)	27	2 years	10	daily	noticeable accent
R(E)M4 (IG)	28	3 years	19	daily	strong accent
R(E)F1 (LW)	21	16 years	5	daily	no accent
R(E)F2 (JM)	27	15 years	7	daily	no accent
R(E)F3 (AF)	20	11 years	7	daily	slight accent
R(E)F4 (BM)	19	5.5 years	11	daily	no accent
R(E)F5 (OD)	26	2.5 years	12	daily	noticeable accent
Speaker-sex-number (initial)	Age at the time of recording	Length of stay in Russia	Age when s/he started to learn Russian	Frequency of speaking Russian with natives	Self-evaluation of Russian pronunciation
E(R)M1 (CS)	25	1 year	19	2-3 times a month	slight accent
E(R)M2 (BL)	23	10 months	20	once two weeks	noticeable accent
E(R)M3 (TR)	27	6 months	19	daily	slight accent
E(R)F1 (LA)	28	14 months	13	rarely	slight accent
E(R)F2 (SP)	29	2 years	18	2 times a month	slight accent
E(R)F3 (KB)	22	4 months	19	once a week	noticeable accent
E(R)F4 (CW)	19	None	19	never	strong accent

2.2. Reading materials and recordings

Speakers read randomized /bVt/ lists in carrier phrases ("Povtori /bVt/ eshche raz (Repeat /bVt/ one more time)" for Russian and "Say /bVt/ to me" for English), where the medial monophthong V contexts were /e, ɑ, u, o/ (*bet*, *bat*, *but*, *bot*) for Russian and /i, ɪ, ɛ, æ, ʌ, u, ɔ, ɑ/ (*beat*, *bit*, *bet*, *bat*, *but*, *boot*, *bought*, *bot*) for English.[1] The Russian vowel /ɨ/ was excluded from the list, because it is produced as a diphthong for which it is difficult to determine the steady state.[2] Three tokens of each test sentence were produced, which amounted to a total of 1152 tokens [12 syllables*2 measurement points*3 repetitions*16 speakers]. The palatalized bilabial stop in Russian was also recorded in the identical vowel contexts in preparation for comparison to the corresponding plain stop later on (see section 3.1 below).[3]

Recordings were made on a Panasonic SV-3800 professional digital audio tape recorder using a Neumann KM184 microphone in a sound-attenuated room in a phonetics laboratory at Stanford University (recordings made in February 2006). The speakers were asked to read the materials first for practice, then for recording. They read a one-paragraph short story in the language to be recorded before reading the target sentences, to help the speakers switch from one language mode to the other. The speakers first read their native language materials, took a break, and then read their non-native language materials. The sentences were converted to WAV files at a 22.05 kHz sampling rate.

2.3. Acoustic analysis

The $F2_C$ and $F2_V$ frequencies of the target words were measured using PCquirer software. The initial formant measurements were obtained from linear predictive coding (LPC) analyses (22.05 sampling rate, 26 coefficients) with each measurement confirmed by cursor frequency readouts on the on-screen wideband spectrograms. The $F2_C$ values were measured at the first glottal pulse after the stop release, and the $F2_V$ values were taken at the steady state. While the $F2_V$ was measured at a fixed time point of 60 msec after the release in [10], this study took variable measurement points for the $F2_V$ depending on configurations of F2 contour shapes like [13] and [14]. If the F2 contour was diagonally rising or falling, a midpoint of the entire vowel duration was

1) Russian materials were given in Russian orthography.

2) In Russian, /ɨ/ occurs only after non-palatalized consonants, and /i/ only after palatalized consonants and word-initially ([18]).

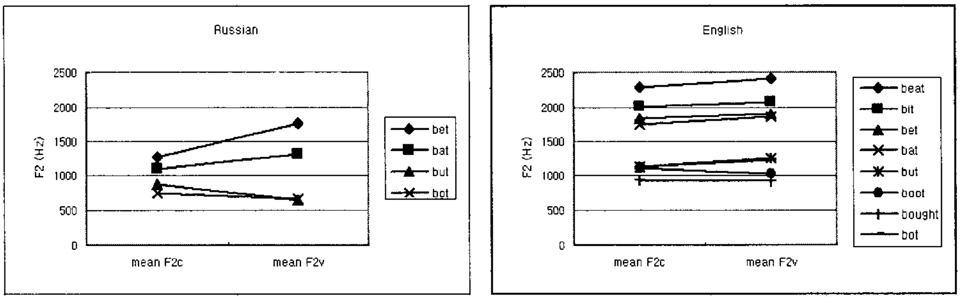
3) Only one place of articulation was investigated to provide more detailed analyses on data. Bilabials were selected because English alveolars exhibit relatively small slopes and therefore alveolars in English and Russian may not show significantly different slopes, and English velars exhibit considerable allophonic variations in slopes depending on front and back vowel contexts ([13], [14], and [19]).

determined, and if the F2 was either U-shaped or the inverse, the minimum or maximum frequency value respectively was chosen as the $F2_V$.

3. Results

3.1. Native speakers of English and Russian

<Figure 1> is a graphic representation of the F2 contour shapes connecting mean $F2_C$ and $F2_V$ values (across three-time repetitions) of the CV syllables used to generate locus equations. The left figure is for a native Russian speaker and the right for a native English speaker.

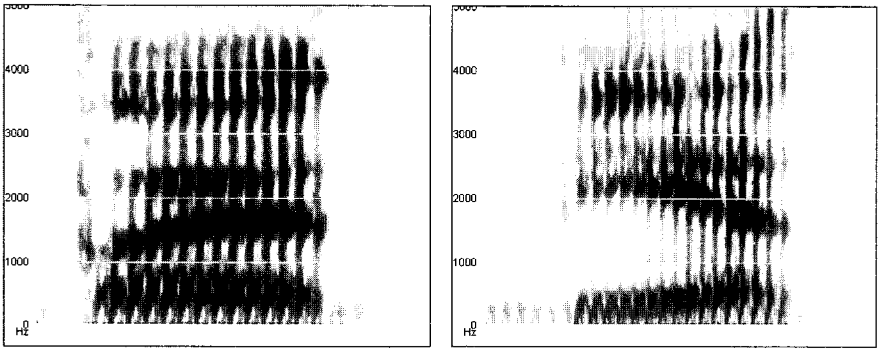


<Figure 1> Schematic representations of $F2_C$ and $F2_V$ values of Russian (left) and English (right) syllables: Examples from RM4(IG) and EM2(BL)

In Russian, the vowel in [bet] recorded the highest $F2_V$, and the vowels in [bot] and [but] the lowest $F2_V$ values. In some speakers, the $F2_V$ of [bot] was slightly higher than that of [but], but in others the $F2_V$ values of the two vowels were indistinguishable. There were no speakers who produced a [but] $F2_V$ higher than that of [bot].

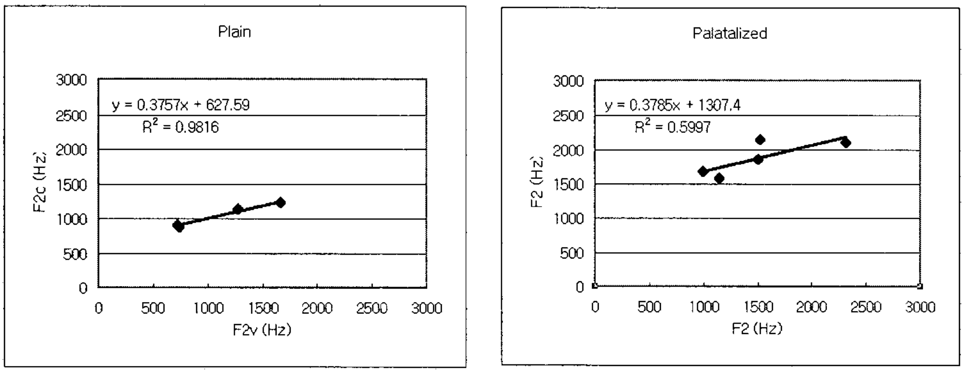
The most notable feature was that the $F2_C$ is considerably low in the context of a front vowel with high F2 (e.g., in [bet]); therefore the F2 contour shape in the syllable drastically rises. For syllables with front vowel contexts, e.g., [bit], [bɪt], and [bɛt], in the right figure, compare the Russian with the English in which rising degrees of the contours are much more sluggish. This means that the consonant values are less affected by the contextual vowel values, i.e., the amount of consonant coarticulation due to vowel contexts is smaller in Russian than in English. It can be interpreted that, as in the case of alveolar consonants in general (see section 1.1

above), the bilabial stop in Russian have relatively fixed locus values. This is understandable in that if the $F2_C$ becomes higher due to the influence of the following front vowels, the distinction of the plain bilabial consonant with the corresponding palatalized bilabial may become less clear. Sample spectrograms of Russian [bet] and [bʲet] are illustrated in <Figure 2>. Note that the F2 of [bet] exhibits a rising contour, making a clear contrast with the F2 contour of [bʲet].



<Figure 2> Sample spectrograms of Russian [bet] (left) and [bʲet] (right): RM2(LB)

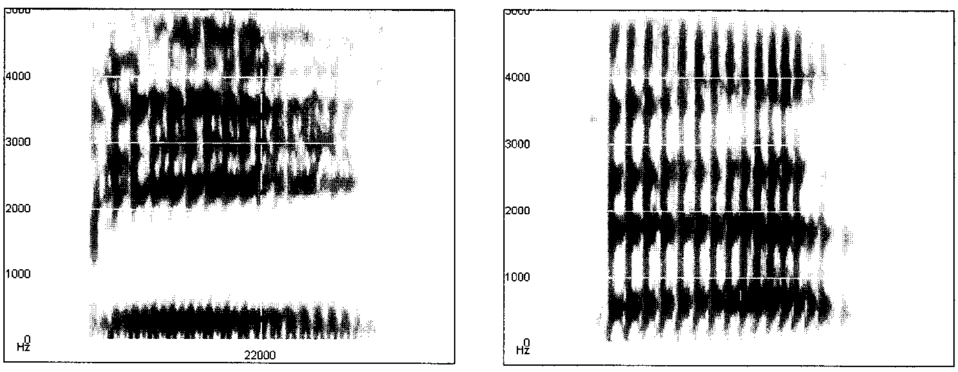
In <Figure 3>, locus equation plots of the Russian plain vs. palatalized bilabial stop are illustrated, as produced by a native Russian speaker (RM2, LB). The slopes of the two equations were very similar (0.3757 vs. 0.3785, respectively), and it seemed that the contrastive distinctiveness between the two places was maintained by the distinct values of y-intercepts (627.59 vs. 1307.4, respectively).



<Figure 3> Locus equation samples of Russian plain (left) and palatalized (right) bilabial stop: RM2(LB)

In English, the vowel F2's of the front vowels ascended in the order [bit] → [bɪt] → [bet] → [bæt], which was consistently found in the production of all native speakers participated. The vowel F2's of the back vowels, however, showed some speaker variations. The vowel F2's ascended in the order [bʌt] → [bɑt] → [but] → [bɔt] in subject EM3(TR), and in the order [bʌt] → [but] → [bɑt] → [bɔt] in EF1(LA). EM2(BL) produced comparable $F2_V$ values in [bʌt] and [bɑt], EF3(KB) in [bɔt] and [bɑt], and EF2(SP) in [but], [bɔt], and [bɑt]. EF4(CW) produced similar $F2_V$ values for [bʌt] and [but], and for [bɔt] and [bɑt]. EM1(CS) produced comparable F2 values for all the four back vowels.

For these native English speakers, the F2 contours generally increased in the context of the front vowels, because the consonant F2's were lower than the F2's of the contextual vowels. However, the degrees of increase were considerably small compared to the Russian contours. As shown in <Figure 1>, even in the English syllable [bit] which had the highest $F2_V$ the F2 contour was comparatively shallow, and the same thing occurred in the other front vowel contexts, i.e., [bɪt], [bɛt], and [bæt]. This suggests that the consonant F2's of the bilabial stop in English are influenced considerably by the F2 values of the contextual vowels, and that the amount of anticipatory coarticulation is large. This may be due to the fact that even if the consonant F2's in English become high due to the influence of the following front vowels, it would not cause any problem in maintaining contrasts with other consonants. Sample spectrograms of English [bit] and [bɛt] are illustrated in <Figure 4>. Notice that the F2 onsets are considerably variable, depending on the vowel F2's which follows. Note also that the vowel F2's in Russian [bet] (in <Figure 2> above) and in English [bɛt] are comparable, but their F2 onsets are quite different.

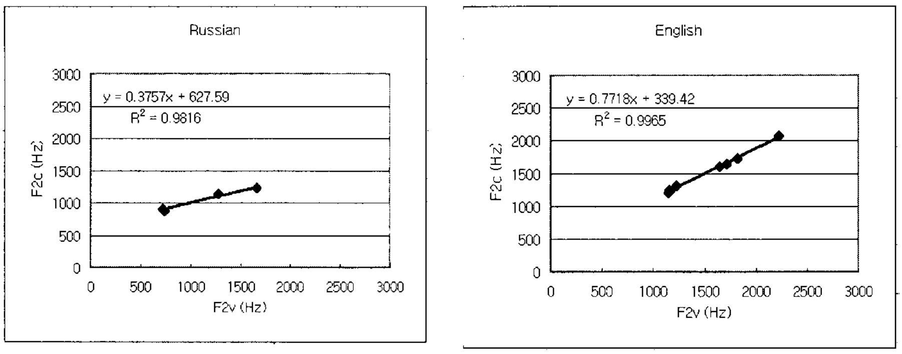


<Figure 4> Sample spectrograms of English [bit] (left) and [bɛt] (right): EM3(TR)

<Table 2> presents locus equation slopes, y-intercepts, and R^2 (the square of the correlation coefficient) values for each subject according to native group, and mean values of the two native groups. The locus equations were generated based on the means of $F2_C$ and $F2_V$ values over three-time repetitions. The slopes were smaller in Russian than in English, and the y-intercepts were overall larger in Russian than in English. The group mean of the Russian slopes was 0.4635 (ranging 0.3054 to 0.5649, 95% CIs = 0.3872 to 0.5399), and that of English was 0.8048 (ranging 0.6917 to 0.9212, 95% CIs = 0.7470 to 0.8626). A *t*-test performed on the slope values showed a significant effect for language ($p < 0.0001$). The group mean of the Russian y-intercepts was 548.60 (ranging 323.58 to 754.51, 95% CIs = 459.61 to 637.59), and that of English was 267.01 (ranging 63.63 to 525.49, 95% CIs = 137.68 to 396.34). Another *t*-test performed on y-intercepts also showed a significant effect for language ($p < 0.005$). The group mean R^2 of Russian was 0.9323 (ranging 0.8562 to 0.9911), and that of English was 0.9793 (ranging 0.9581 to 0.9965), indicating that the locus equations produced by the native speaker groups were highly linear. (Locus equations obtained with raw data points produced mean R^2 values of 0.8634 (ranging 0.7304 to 0.9599) for Russian and 0.9610 (ranging 0.9388 to 0.9826) for English.) <Figure 5> below presents sample locus equations of the Russian and English bilabial stop. Note the differences in slopes and y-intercepts between the two languages.

<Table 2> Locus equation slopes, y-intercepts, and R^2 values of Russian and English bilabial stops produced by native speakers

speaker (initial)	slope	y-intercept	R^2	speaker (initial)	slope	y-intercept	R^2
RM1 (AI)	0.5470	384.75	0.9911	EM1 (CS)	0.7718	339.42	0.9965
RM2 (LB)	0.3757	627.59	0.9816	EM2 (BL)	0.9212	63.63	0.9867
RM3 (DL)	0.3832	584.34	0.8812	EM3 (TR)	0.7718	264.03	0.9581
RM4 (IG)	0.4092	551.69	0.9406	EF1 (LA)	0.8633	166.08	0.9699
RF1 (LW)	0.5078	505.41	0.8562	EF2 (SP)	0.6917	525.49	0.9763
RF2 (JM)	0.4037	684.27	0.9384	EF3 (KB)	0.7593	426.90	0.9838
RF3 (AF)	0.6745	323.58	0.9904	EF4 (CW)	0.8548	83.49	0.9839
RF4 (BM)	0.3054	754.51	0.9544	Mean	**0.8048**	**267.01**	**0.9793**
RF5 (OD)	0.5649	521.30	0.8564				
Mean	**0.4635**	**548.60**	**0.9323**				

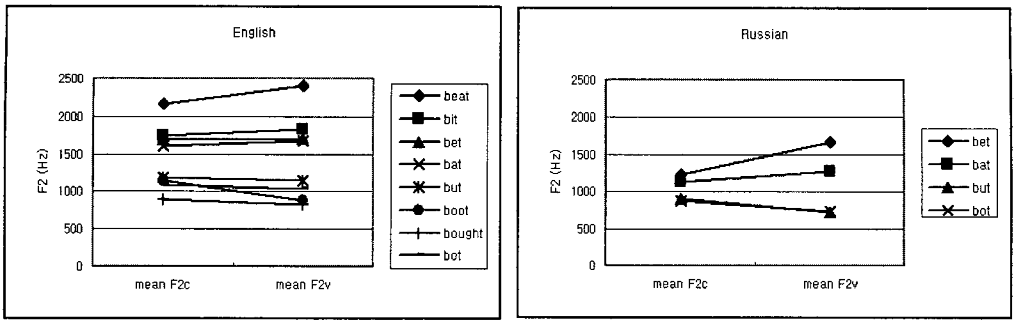


<Figure 5> Sample locus equations of Russian (RM2, left) and English (EM1, right)

Since the locus equation metric compares the consonant F2's relative to the vowel F2's, there is no need to normalize and compensate despite the cross-gender difference in vocal tract size, as pointed out in [13] and [14]. To ascertain the claim, however, slopes and y-intercepts of male and female speakers were compared, using *t*-tests. Mean slopes, for male and female speakers respectively, were 0.4288 and 0.4913 for Russian (p = 0.4367), and 0.8216 and 0.7923 for English (p = 0.6713), and no significant differences were found in slope means as a function of gender. Mean y-intercepts, for male and female speakers respectively, were 537.09 and 557.81 for Russian (p = 0.8288), and 222.36 and 300.49 for English (p = 0.5831), and the differences were also found not to be significant, either. It can be concluded, then, that while female speakers exhibited higher F2 values due to the differences in vocal tract size, the relation between consonant F2's and coarticulated vowel F2's is not affected by differences in absolute frequency values ([13] and [14]).

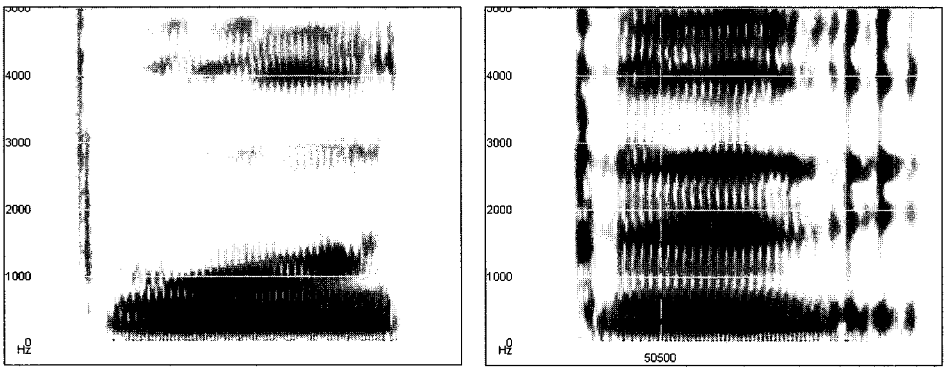
3.2. Russian speakers of English

For the English syllables produced by native Russian speakers, six out of nine speakers produced the front vowels with high F2v values, ascending in the order [bit] → [bɪt] → [bet] → [bæt], which is exactly the pattern demonstrated by native English speakers. In one speaker, REM4(IG), the vowel F2's in [bit] and [bɪt] were not distinct enough, and in speakers REM1(AI) and REF5(OD), almost no difference was shown between the F2 values of the two high front vowels. Moreover, the speaker REM3(DL) produced lower F2v's for [bet] than for [bæt]. Graphic representations of the F2 contour shapes connecting the mean F2c and F2v values of the English (left) and Russian (right) CV syllables produced by a Russian speaker are compared in <Figure 6>.



<Figure 6> Schematic representations of mean $F2_C$ and $F2_V$ values of English (left) and Russian (right) syllables produced by a native Russian speaker (REM2, LB)

Distributions of the central and back vowels in [bʌt], [but], [bɔt], and [bɑt] showed larger variations across learners. The vowel F2's in [but] produced by REF1(LW) and REF4(BM) were the highest among the four central and back vowels. Sample spectrograms in <Figure 7> compare the Russian and English [but] in REF1(LW). Note that the vowel F2 of her Russian [but] is around 1000 Hz, but that of her English [but] is more than 1500 Hz. This result indicates (1) that the speaker successfully acquired the tendency of fronting (and/or lip spreading) the English high back vowel [u], which is one of the major changes occurring in recent American English (e.g., [20]), and (2) that the acquisition of higher consonant F2 values for English accompanied by the acquisition of the higher vowel F2's evidences non-native acquisition of proper coarticulation. On the other hand, speakers REM1(AI) and REM3(DL) demonstrated both low vowel and consonant F2's for the English [but], which shows the influence of the native Russian [but].

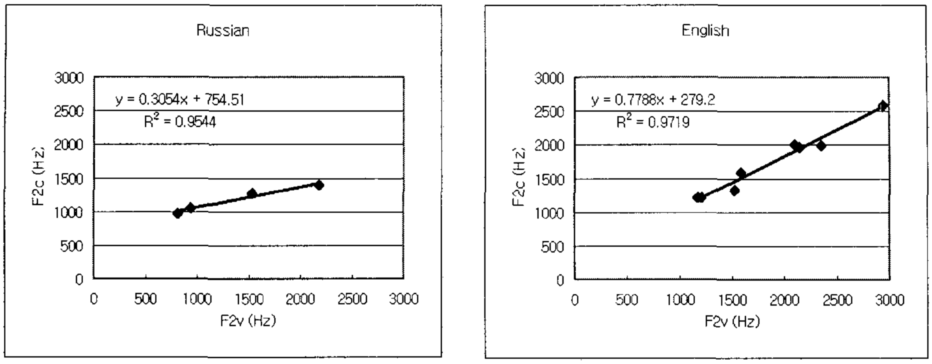


<Figure 7> Sample spectrograms of Russian and English [but] in REF1(LW)

<Table 3> presents locus equation slopes, y-intercepts, and R^2 values of Russian and English produced by native Russian speakers. As for the grand mean, they produced a drastically increased slope for English (0.7852) compared to Russian (0.4635). As well as the mean values, every individual speaker produced larger slopes for English than for Russian. The y-intercepts were drastically reduced from 548.60 for Russian to 284.29 for English, also approaching the L2 norms (i.e., typical values that native speakers produce). Notice that even for English, their non-native language, they exhibited an extremely high mean R^2 value of 0.9725 (ranging 0.9496 to 0.9846). (Locus equations obtained with raw data points produced a mean R^2 value of 0.9619 (ranging 0.9414 to 0.9815) for non-native English.) <Figure 8> presents sample locus equations for both Russian and English, produced by a native speaker of Russian (REF4, BM); through it, one can easily see the contrast in slopes (0.3054 vs. 0.7788) and y-intercepts (754.51 vs. 279.2) between the subject's native Russian and non-native English.

<Table 3> Locus equation slopes, y-intercepts, and R^2 values of Russian and English produced by native Russian speakers

	Russian			English		
speaker (initial)	slope	y-intercept	R^2	slope	y-intercept	R^2
REM1 (AI)	0.5470	384.75	0.9911	0.9033	112.58	0.9779
REM2 (LB)	0.3757	627.59	0.9816	0.7655	338.66	0.9778
REM3 (DL)	0.3832	584.34	0.8812	0.7043	322.48	0.9776
REM4 (IG)	0.4092	551.69	0.9406	0.7706	254.43	0.9496
REF1 (LW)	0.5078	505.41	0.8562	0.8333	240.64	0.9708
REF2 (JM)	0.4037	684.27	0.9384	0.7899	273.49	0.9703
REF3 (AF)	0.6745	323.58	0.9904	0.7799	347.71	0.9846
REF4 (BM)	0.3054	754.51	0.9544	0.7788	279.20	0.9719
REF5 (OD)	0.5649	521.30	0.8564	0.7410	389.45	0.9718
Mean	**0.4635**	**548.60**	**0.9323**	**0.7852**	**284.29**	**0.9725**

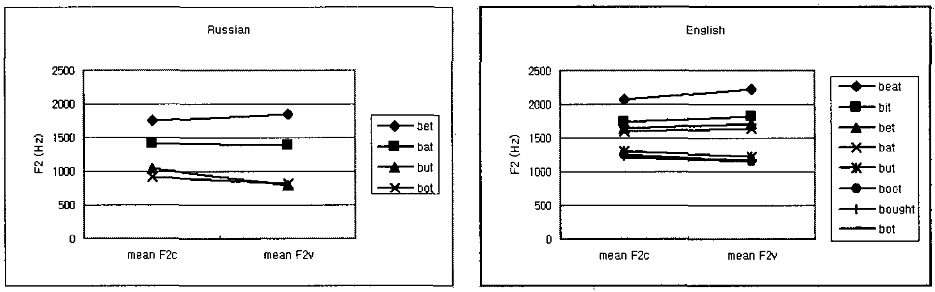


<Figure 8> Sample locus equations of Russian (left) and English (right) produced by a native Russian speaker (REF4, BM)

3.3. English speakers of Russian

As for Russian syllables produced by native English speakers, the $F2_V$ values increased in the order [bet] → [bat] → [bot] or [but]. Unlike their Russian counterparts, some English speakers produced the Russian [but] with higher $F2_V$ values than [bot] (e.g., ERM2, ERM3, ERF4). This can be interpreted as a native English influence on their articulation of non-native Russian, since the F2's of the English vowel [u] are considerably high (as discussed in section 3.2).

A more noteworthy difference between native and non-native Russian speakers was that for the latter, the consonant F2's of [bet] showed significantly large degrees of coarticulation with contextual vowel F2's. In <Figure 9> which shows the example of ERM1, both the mean vowel and consonant F2's of his Russian [bet] are analogous to those of his English [bɪt]. This suggests that his non-native production was influenced by the amount of anticipatory coarticulation in his native language.



<Figure 9> Schematic representations of mean $F2_C$ and $F2_V$ values of Russian (left) and English (right) syllables produced by a native English speaker (ERM1, CS)

Another interesting result is that, in his production of Russian [but], subject ERM1 successfully lowered his consonant F2 as well as vowel F2, as seen in <Figure 9>. This can be interpreted as the learner's transfer of the degree of CV coarticulation from his native English to his Russian.[4]

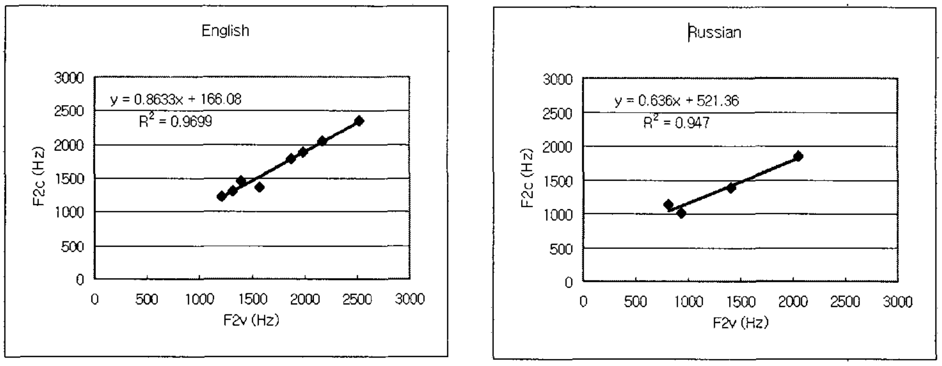
<Table 4> presents locus equation slopes, y-intercepts, and R^2 values of English and Russian produced by native English speakers. While the mean slope for English was 0.8048, the mean slope for Russian was 0.7637, which is a slight shift toward the L2 norm. However, individual speakers revealed some variations. ERM3(TR), ERF2(SP), and ERF3(KB) displayed larger slope values for Russian than for English, and ERM1(CS) and ERF4(CW) exhibited little differences between the slopes of English and Russian. The y-intercepts increased from the mean of 267.01 for English to the mean of 315.61 for Russian, demonstrating a slight change towards the L2 standard. Note that the native speakers of English also recorded very high R^2 values when producing their non-native Russian (mean 0.9775, ranging 0.9470 to 0.9941). (Locus equations obtained with raw data points produced a mean R^2 value of 0.9500 (ranging 0.9066 to 0.9804) for non-native Russian.) Note especially that ERM2(BL) and ERF1(LA) who exhibited comparatively clear differences between the slopes of their native and non-native languages exhibited very high R^2 values (0.9688 and 0.9470, respectively). This is important because, when native and non-native slopes are similar, high non-native R^2 values can result just from the transfer of native degrees of anticipatory coarticulation in all syllables.

4) This interpretation was made under the assumption that it is difficult to imagine his learning only the $F2_C$ of this syllable while not learning the $F2_C$'s of the other syllables. However, as a reviewer pointed out, we cannot exclude the possibility that the speaker learned the native speaker pattern successfully only in this syllable.

<Table 4> Locus equation slopes, y-intercepts, and R^2 values of English and Russian produced by native English speakers

	English			Russian		
speaker[5] (initial)	slope	y-intercept	R^2	slope	y-intercept	R^2
ERM1 (CS)	0.7718	339.42	0.9965	0.7410	384.65	0.9716
ERM2 (BL)	0.9212	63.63	0.9867	0.6826	261.58	0.9688
ERM3 (TR)	0.7718	264.03	0.9581	0.8042	218.87	0.9870
ERF1 (LA)	0.8633	166.08	0.9699	0.6360	521.36	0.9470
ERF2 (SP)	0.6917	525.49	0.9763	0.7070	419.49	0.9809
ERF3 (KB)	0.7593	426.90	0.9838	0.9537	178.87	0.9933
ERF4 (CW)	0.8548	83.49	0.9839	0.8214	224.42	0.9941
Mean	**0.8048**	**267.01**	**0.9793**	**0.7637**	**315.61**	**0.9775**

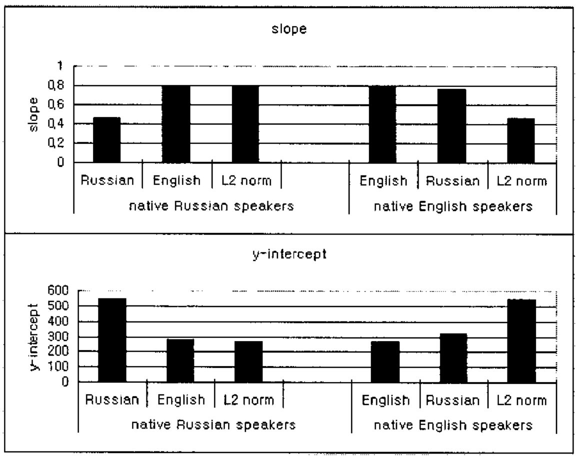
<Figure 10> shows sample locus equations produced by a native speaker of English (ERF1, LA), who displayed comparatively clear distinctions between English and Russian. The slope was reduced for Russian (0.6360) compared to English (0.8633), and the y-intercept was increased for Russian (521.36) compared to English (166.08).



<Figure 10> Sample locus equations of English (left) and Russian (right) produced by a native English speaker (ERF1, LA)

5) ERM2(BL), ERM3(TR), and ERF3(KB) produced palatalized [bʲɛt]'s over all three-time repetitions in place of [bet], which made it impossible to use to generate locus equations of the plain bilabial stop. Therefore, their locus equations were derived using only [bɑt], [but], and [bot].

To summarize sections 3.2 and 3.3, for Russian speakers of English, the slopes were drastically increased and the y-intercepts were reduced from native Russian (slope: 0.4635, y-intercept: 548.6) to non-native English (slope: 0.7852, y-intercept: 284.29). For English speakers of Russian, the slopes were reduced and y-intercepts were increased from native English (slope: 0.8048, y-intercept: 267.01) to non-native Russian (slope: 0.7637, y-intercept: 315.61). As illustrated in <Figure 11>, Russian speakers of English successfully approached the L2 norms in both the slope and y-intercept values, while English speakers of Russian exhibited only slight shifts towards the L2 norms in the two parameter values.



<Figure 11> Graphic representations of mean slope and y-intercept values produced by Russian speakers of English and English speakers of Russian

4. Summary and discussions

The locus equation scatterplots for [bilabial stop + vowel] syllables obtained from 16 native speakers of English and Russian exhibited extreme linearity: The group mean R^2 of English was 0.9793, and that of Russian was 0.9323. The slope values were significantly smaller in Russian than in English, and the y-intercepts were larger in Russian than in English. For Russian speakers of English, the slopes were drastically increased and the y-intercepts were reduced from native Russian to non-native English, approaching the L2 norms in the two parameter values. For English speakers of Russian, the slopes were reduced and y-intercepts were increased from native English to non-native Russian, exhibiting slight shifts towards the L2 norms. Simply put, the results reported in [17] were basically reverified.

One of the questions asked was whether the locus equation metric would be able to reveal developmental changes in V-to-C coarticulation effects in non-native speakers. One trend towards such a conclusion is found in the fact that Russian speakers displayed significant changes toward the L2 norms both in slopes and y-intercepts, while English speakers failed to do so. This is understandable considering the fact that the Russian speakers who participated in this experiment had significantly more naturalistic exposure to L2 than did the English speakers. A second indication was improvement in slopes and y-intercepts for more experienced speakers compared to less experienced speakers. In Group RE, more experienced speakers (REM1, REM2, REF1, REF2) displayed better approximations to the L2 norms than less experienced speakers (REM3, REM4, REF4, REF5) both in slopes (mean 0.823 vs. 0.749, respectively) and y-intercepts (mean 241.3 vs. 311.4, respectively). Also in Group ER, more experienced speakers (ERM1, ERF1, ERF2) better approached L2 standards than less experienced speakers (ERM3, ERF3, ERF4) both in slopes (mean 0.695 vs. 0.860, respectively) and y-intercepts (mean 441.8 vs. 207.4, respectively). An important articulatory skills in reaching native phonological patterns may involve learning when to reduce coarticulation and when to increase it. It appears that the fine tuning that goes on during articulation-related foreign-language experiences allows learners to gain control over the proper levels of coarticulatory variations.

Another question asked was whether L2 locus equations would exhibit linearity. Every one of the non-native locus equations generated by Russian speakers exhibited linearity, all R^2 values exceeding 0.90. The locus equations of Russian produced by native speakers of English also recorded extremely high R^2 values (mean 0.9775). Then, a question arises whether the highly linear relationships are physically inevitable. [21] investigated the output of the prelinguistic child, and reported locus equations derived from one infant in its babbling stage. The relationship between F2 onsets and vowel F2's was noisy, and the prelinguistic CV utterances of this infant turned out not to conform to the typical locus equation patterns (cf. [14]). [21] reported that the scatterplots of developmental-apraxia-of-speech (DAS) children did not cluster tightly around the regression line, with R^2 values ranging from only 0.25 to 0.70. If the locus equations can be nonlinear and noisy as shown by the samples from the prelinguistic child and DAS children, this would support the claim that the development of normal motor control strategies is required to produce the typical form of locus equations. Once the motor control systems are acquired, however, the linear patterns of the locus equations could become a universal linguistic feature. The objective of the adult non-native speakers is then to develop the strategy adjusting the overall slope and y-intercept variations for L2. This may provide a clue for the claim that the unit of phonetics acquisition in non-native speakers is the locus equation parameters (i.e., slopes and y-intercepts). If acquisition occurs in the unit of individual CV-by-CV syllables, then the L2 locus equations may turn out not to be so linear.

Another implication of this study relates to the phonetic vs. phonological approaches to language acquisition. As [22] states, "[t]wo- and three-dimensional representations of acoustic phonetic space show that relational (not absolute) and variably-valued (not binary) parameters provide a more realistic view of how phonemic categories are developmentally organized and eventually represented (from [14: p. 778])." The virtual acoustic phonetic space in which acquisition occurs is not analogous to abstract, absolute, and dichotomous feature systems that many phonologists prefer. Then, the phonological approaches do not appear to appropriately take into account the facts that the phonological categorization is structured through gradual developmental processes. This further shows that the existing sound learning hypotheses at the level of phonemes need to be reconsidered and that perception- and articulation-related learning for the allophonic variations determined by adjacent phonetic environments are necessary.

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