ISSN 2005-8063
2016. 9. 30.
Vol.8 No.3
pp. 11-20

말소리와 음성과학

Phonetics and Speech Sciences

한국음성학회지

http://dx.doi.org/10.13064/KSSS.2016.8.3.011

Variation in vowel duration depending on voicing in American, British, and New Zealand English*

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Abstract

It is well known that vowels are shorter before voiceless consonants than voiced ones in English, as in many other languages. Research has shown that the ratio of vowel durations in voiced and voiceless contexts in English is in the range of 0.6~0.8. However, little work has been done as to whether the ratio of vowel durations varies depending on English variety. In the production experiment in this paper, seven speakers from three varieties of English, New Zealand, British, and American English, read 30 pairs of (C)VC monosyllabic words which differ in coda voicing (e.g. *beat-bead*). Vowel height, phonemic vowel length, and consonant manner were varied as well. As expected, vowel-shortening effects were found in all varieties: vowels were shorter before voiceless than before voiced codas. Overall vowel duration was the longest in American English and the shortest in New Zealand (NZ) English. In particular, vowel duration before voiceless codas is the shortest in New Zealand English, indicating the most radical degree of shortening in this variety. As a result, the ratio of vowel durations in varying voicing contexts is the lowest in NZ English, while American and British English do not show a significant difference each other. In addition, consonant closure duration was examined. Whereas NZ speakers show the shortest vowel duration before a voiceless coda, their voiceless consonants have the longest closure duration, which suggest an inverse relationship between vowel duration and closure duration.

Keywords: pre-fortis clipping, voicing, vowel duration, New Zealand English, British English, American English

1. Introduction

1.1. Pre-fortis clipping (PFC)

It is well known that vowels are generally shorter before a voiceless consonant than before a voiced consonant in many languages (Chen, 1970; Keating, 1985). In English, it is said that vowels are shortened, or 'clipped', before a voiceless coda. This is known as prefortis clipping (PFC, hereafter) (House & Fairbanks, 1953; Chen, 1970; Lisker, 1974: 229; Peterson & Lehiste, 1960; Keating, 1985; Gimson, 1989:96-97; Wells, 1990; Roach, 2010:28). For example, the vowel in beat [bi:t] is phonetically shorter than the vowel in bead [bi:d], though the vowels are the same, high front long vowel /i:/ in their phonological representation. In English, the ratio of vowel duration before a voiceless consonant and vowel duration before a voiced consonant (hereafter, 'PFC ratio') is roughly about in the range of 0.61~0.79. The ratio is 0.75 in Sharf (1962), i.e., vowels before a voiceless consonant are 75% shorter than those before a voiced consonant. Other research reports 0.69 (House & Fairbanks, 1953), 0.66 (Peterson & Lehiste, 1960:700), 0.61 (Chen, 1970), and 0.79 (Klatt, 1973). Research has shown that though PFC itself is found in most languages, PFC ratio may differ in different languages (Chen, 1970:138): English (0.61), Korean (0.78), Russian (0.82), Norwegian (0.82), Spanish (0.86), French (0.87). Though rarely, there is a language where PFC is not robust: in Saudi Arabic,

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Received 6 August 2016; Revised 16 September 2016; Accepted 20 September 2016

vowels are not significantly longer before voiced than before voiceless consonants (Flege, 1979). According to de Jong and Zawaydeh (2002:56), in Arabic, voicing-depending vowel shortening was significant in some literature (Port *et al.*, 1980; Munro, 1993), but not in others (Frege & Port, 1981; Mitleb, 1984a). De Jong and Zawaydeh (2002) reported that in Ammani-Jordanian Arabic, the voicing effect was 'not quite significant' ($p<0.1$) across subjects, though the effect was significant in each speaker (p. 61). Czech and Polish, both West Slavic languages, also fail to exhibit vowel shortening effect in voiceless context (Keating, 1985). In Polish, the ratio is 1.0, indicating no vowel shortening effect. In Czech the ratio is 0.98 but the two vowel durations were not significantly different.

Compared to other languages, English is a language that has rather lower, if not the lowest, PFC ratio, which means there is a relatively larger difference between vowel durations before voiceless consonant vs. before voiced consonant. Given the differences found across languages, Keating (1985) argued that vowel shortening before voiceless consonant cannot be physiologically-determined phonetic universal (contrary to Chomsky & Halle, 1968). Instead, languages that exaggerate shortening (like English) or languages that lack shortening (like Arabic and West Slavic languages) must have language-specific rules. Other languages that do not have exaggerated patterns have no such language-specific rules, and vowel duration is determined in the universal phonetic component in such languages.

In the previous work, differences in PFC that may arise from different regional dialects were understudied, despite the existence of various varieties of English. For example, Peterson and Lehiste (1960) studied American English by recording five speakers of the same dialect. If PFC ratio varies across languages as the previous literature suggests, it is also conceivable that different dialects of the same language may also exhibit differences in the ratio of vowel durations. It can also be imagined that languages that are typologically closer would show similar PFC ratios, whereas languages that are typologically remote would show greater differences in PFC ratios. However, the mentioned previous work already disproves this (Korean (0.78) is in between English (0.61) and French (0.87) (Chen, 1970). Nevertheless, if admitting that English is exceptional in terms of vowel shortening as just mentioned, taking English aside, to a degree it seems true that typologically similar languages could exhibit similar ratios (Spanish (0.86), French (0.87) (Chen, 1970) - both Romance languages; West Slavic languages do not show great PFC effects (Keating, 1985)). If the latter is true, it is plausible that varieties of one language would show similar ratios among them, since varieties of one language belong to the same language. The present study aims at testing these hypotheses by looking at vowel shortening patterns of three varieties of English: American, British (of Northern England, Manchester region) and New Zealand English. If, as Keating (1985) suggests, different varieties of English undergo the same language-specific phonetic rule of vowel shortening, the PFC ratios are not expected to vary considerably across English varieties. If PFC ratios vary substantially depending on dialects, it could mean that phonetic rules could be different even in different dialects of the same language.

One previous study on dialectal differences in English vowel shortening is Tauberer & Evanini (2009). They compare the ratio of vowel duration in voiced/voiceless environment across various dialects of North American English. They collected duration data measurements from the Atlas of North American English corpus (telephone interviews), including 12 major North American dialects. They found that ratio of vowel duration falls in the range of 0.79-0.88 (taking the inverse of 1.33 and 1.02 – They used duration ratios of vowels before a voiced coda to vowels before a voiceless coda.). Only Boston (0.75) and Maine (0.98) were outliers. Maine's ratio 0.98 was higher than any numbers that have reported in the literature, but the interaction of voicing and dialect was not significant for Maine.

In addition to vowel duration, this paper will examine closure durations of voiceless and voiced consonants, and their ratios (voiceless to voiced) in the three varieties of English. Closure duration is generally longer in voiceless consonants than in voiced consonants (Luce & Charles-Luce, 1985), whereas vowel duration is shorter before a voiceless coda than before a voiced coda. For this reason it has been suggested that there can be an inverse relationship between vowel duration and closure duration of the post-vocalic consonant (Chen, 1970; Keating, 1985:122). In this paper it will be examined whether and how such relationships between vowels and durations hold in different varieties of English.

1.2. New Zealand English (NZE) in relation to British and American English

NZE used to be similar to RP (Standard Southeastern English) since original settlers in New Zealand were mostly Australian and British. Gordon & Deverson (1998) regard it as a "mixing bowl" as New Zealand has had settlers with various accents, Australian (primarily), Scottish, Irish, and RP English. However, it has lost some characteristics of RP recently. Recent research suggests that New Zealand speakers tend to prefer American or even Australian accents, and the prestigious model is now American English rather than RP (Bayard, 2000:4-5).

In NZE, /ɪ/ is very centralized, approaching /ə/, similar to South African English (South African English and New Zealand English are highly close, since South Africa is settled roughly at the same time as New Zealand (Bayard, 2000:2)). The /æ/ and /e/ vowels are higher in New Zealand than in Australian (Bayard, 2000:3). NZE is known for the vowels that are produced with a narrow mouth. The TRAP vowel (e.g. *sa̲t, ba̲t*) is raised, so it is often confused with the DRESS vowel (e.g. *se̲t, be̲t*). The DRESS vowel is also raised to the KIT vowel or even to FLEECE vowel (Gordon, 2013).

In brief, NZE has been largely similar to RP but it is more and more being influenced by American English in the past few decades. Thus it is interesting to examine which variety of English the phonetic details (contextual vowel duration and duration ratios) of NZE are more similar to, British or American English, or neither.

The organization of the paper is as follows: Section 2 describes the experimental method. Section 3 lays out the results in the following order. In Section 3.1, vowel formant plots are provided in order to get an overview of the vowel qualities of the vowels produced by each speaker, where one can check region- or speaker-dependent variations of certain vowels. Section 3.2 provides the analysis of vowel duration, and Section 3.3 analyzes the ratio of the vowels before voiced vs. voiceless codas, in particular whether the ratio varies depending on dialect. Section 3.4 examines closure duration and ratio of closure duration (voiced to voiceless consonants), and the relationships between vowel duration and closure duration are examined across dialects.

2. Method

2.1. Participants

The speakers were three New Zealanders (N1, N2, N3) ('NZ'), two British (B1, B2) ('UK'), and two American speakers (A1, A2) ('US')[1]. All were professors in the College English department, teaching college English to undergraduate Korean students. All were male except N1. B1 is from Bolton (near Manchester) and B2 is from Manchester. A1 is from Indianapolis and A2 is from Upstate New York. None of them reported speaking or hearing problems. The speakers were compensated for their participation.

2.2. Speech materials

The speech materials are selected referring to Hogan and Rozsypal (1980: 1765) and Roach (2010: 174-175). The materials are the same as in Cho (2015), which is shown in Table 1 (the table is reproduced from Cho (2015:119)). The materials consist of 30 minimal pairs of English monosyllabic words (C_1VC_2) that minimally contrast in the voicing of the coda consonant (C_2) (e.g. *beat-bead*). The onset and the vowel were the same in the words in each pair. A wide range of consonants and vowels were included in the speech materials in order to test contribution of various segmental factors, as well as robustness of vowel shortening due to consonant voicing. A few vowels that are subject to regional variation were also included (e.g. h<u>a</u>lf, c<u>o</u>p)[2].

The consonants were varied in voicing (voiceless and voiced), manner (fricative, stop, affricate), and place of articulation. Stops were labial, coronal, and velar (e.g. *beep*, *beat*, *leak*). Fricatives were labio-dental and alveolar, e.g. *leaf, peace*, and affricates were all alveolar.

The vowels were varied in vowel height and phonemic vowel length, because both vowel height and phonemic vowel length can affect phonetic vowel duration. Vowel duration is related to vowel height, which is called 'intrinsic vowel duration' (Lehiste, 1970; Westbury & Keating, 1980). Low vowels tend to be longer than high vowels. Thus, vowel height needs to be taken into account in the analysis of vowel duration as one of the predictors. In this paper, phonemic vowel length indicates the long and short vowel contrast in English (e.g. /iː/-/ɪ/ *beat-bit*). Phonemically short vowels are generally shorter than phonemically long vowels (Hillenbrand *et al.*, 1995:3103). Vowels in the speech materials were thus varied in both height and phonemic vowel length: high vowels (long /iː/ and short /ɪ/) and non-high vowels (long /ɔː/ and short /ɑ/, /ɒ/, /æ/). Diphthongs /oʊ/ and /eɪ/ were included for more variety, but these are not analyzed in statistical testing because of the problems assigning vowel height values for them.

Table 1. Speech materials. (a): stop codas, (b): fricative codas, (c):affricate codas

		High		Non-High		Diphthongs
		Long /iː/	Short /ɪ/	Long /ɔː/ Short /ɑ/, /ɒ/	Short /æ/	
(a)	p-b	beep beeb	rip rib	cop cob	cap cab	rope robe
	t-d	beat bead	bit bid	cot cod	bat bad	coat code
	k-g	leak league	pick pig	clock clog	sack sag	broke brogue
(b)	f-v	leaf leave	riff riv	off of	half have	safe save
	s-z	peace peas	hiss his	sauce saws	ass as	place plays
(c)	ts-dz	beats beads	bits bids	cots cods	pats pads	coats codes

The vowels /ɑ/ and /ɒ/ vary in different accents: e.g. in words such as *cop* and *cob*, the vowel is /ɑ/ in American English, /ɒ/ in British (Carr, 2013) and New Zealand English. Such words also include *cot-cod*, *clock-clog*, *cots-cods* in the third column of the words in the table. The vowel in *off* is /ɔː/ (long) in American English, whereas it is /ɒ/ (short) in British and New Zealand English. The vowel in *of* is phonemically short vowel in all accents. The vowel in *sauce* and *saws* is long /ɔː/ Further variation is found with the pair *half-have*. American speakers produced these two words with the same vowel /æ/ (short). British speakers and two NZ speakers (N1, N2) produced the vowel in *half* as /ɑː/, whereas N3 read it with /æ/. It also turns out that one NZ speaker (N1) read *ass* with vowel /ɑː/, instead of /æ/. The long or short values of phonemic vowel length were coded in the data sheet accordingly.

Materials with diphthongs were not included in the analysis because their value for vowel height cannot be specified, which causes problems in statistical testing. Thus the words with diphthongs only served as fillers. Analyses including diphthongs were also carried out, but there were no notable differences qualitatively as well as quantitatively compared to analyses excluding diphthongs, so those will not be reported in this paper.

2.3. Recording procedure

The speakers were asked to read the speech materials three times (the whole list were repeated three times, rather than individual words) in a sound-treated recording studio. The speech materials were presented on a sheet of paper to the speaker, in a randomized order. The words were read in isolation, and speakers were asked to put a pause between words. The speakers have a chance to go over the words so that they can check whether there are any unfamiliar words. Some speakers indicated that they are not familiar with the

1 The recordings of American speakers (A1, A2) are the same recordings used in Cho (2015). Some of the measurements were re-done for consistency in the measurement criteria with the other speakers' data analyzed in this paper.

2 A reviewer commented that it would be more effective to use words that do not vary across dialects. In effect, such words are a subset of our speech materials in this paper. I tried to include a variety of words with various conditions, in order to prevent recorded speech from becoming too mechanical, as well as to test segmental factors that influence PFC. Regardless of whether a vowel in question varies across dialects, each vowel was assigned a [long] or [short] feature according to how they are produced by each speaker, so the patterns of variation are included in the statistical analysis.

words *beeb* (a slang for BBC), *riv* (a short form for *river*), and *brogue* (a kind of shoes or Irish accent). All speakers, except N3, had no problem pronouncing these after a preview. N3 showed a difficulty pronouncing *brogue* during the recording, producing them with a trill [r] and a heavily devoiced [g] with hesitation and self-correction. The sounds were recorded on a PC through a mastering device, using Sound Forge (with sampling frequency 44.1kHz, sampling size 16 bit). One American speaker (A2) was recorded using Sony IC recorder (ICD-PX312) in a quiet room.

2.4. Measurement and analysis

Vowel duration, closure duration (for stops and affricates) and release duration were measured manually using Praat (Boersma & Weenink, 2016). Figure 1 shows the example of *beep* and beeb. The vowel interval was taken where all the formants are clearly visible. The closure interval is from the end of the vowel to the beginning of the closure, which was visible from the spectrogram.

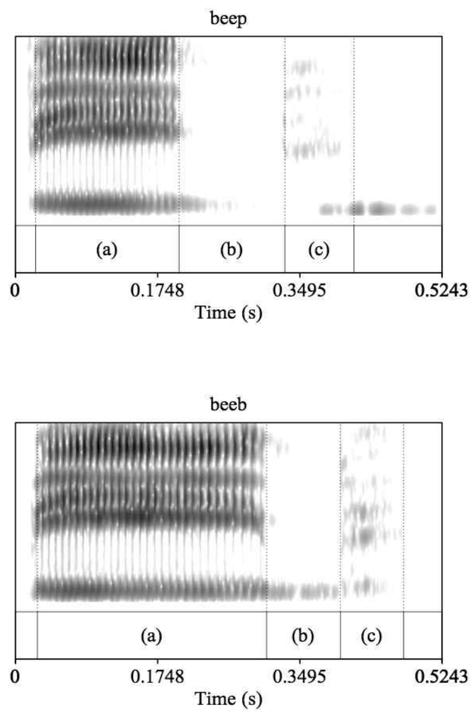


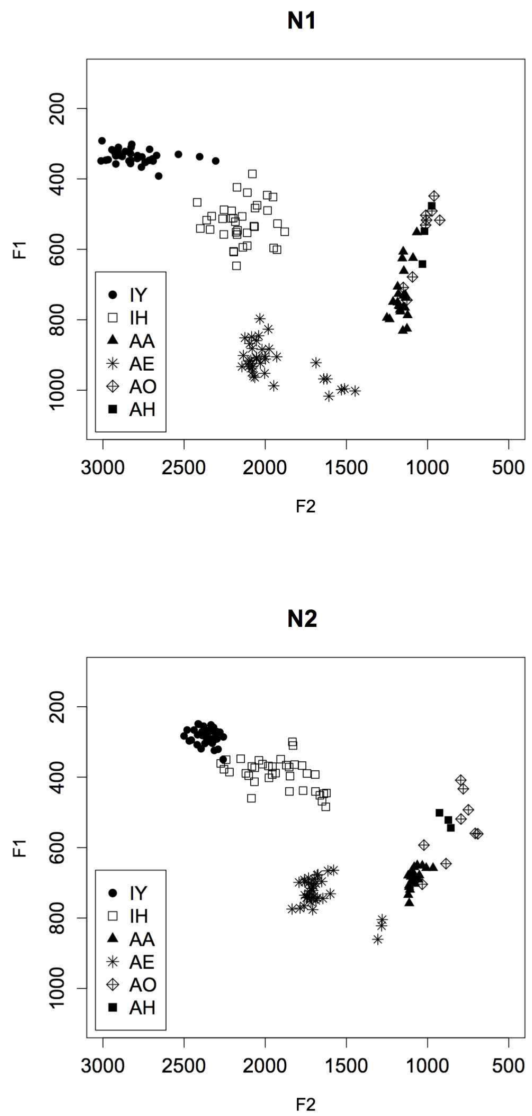
Figure 1. Examples of segmentation of *beep* (top) and *beeb* (bottom). The same temporal interval (524 ms) is taken to make the comparison easier . (a) vowel duration, (b) closure duration , and (c) release duration.

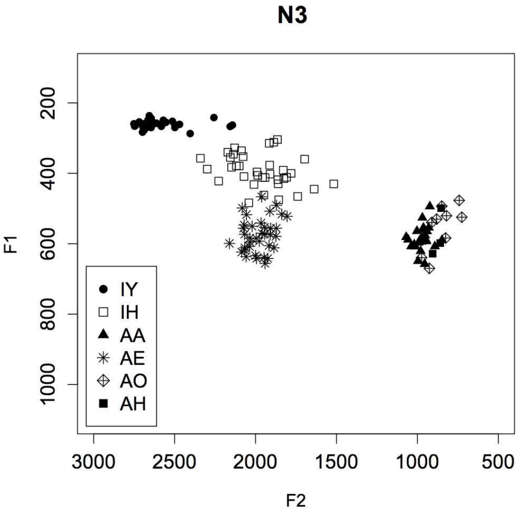
After segmentation, duration data were collected automatically using Praat scripts (Lennes, 2003). Vowel formant data were collected at the midpoint of a vowel using Praat scripts (Lennes, 2003). R statistical software was used for statistical analyses. The R package *lme4* (Bates *et al.*, 2015) was used for linear mixed-effects regression analyses. In mixed-effects linear regression models, there are fixed effects and random effects (Pinheiro & Bates, 2000; Baayen, 2008; Baayen *et al.*, 2008). Participants and words are typically treated as random effects, since they are selected randomly from the population. In this paper we allow random slopes for participants and words, so that the effects of fixed effects (voicing, region, phonemic vowel length, vowel height, manner) can be accurately estimated after factoring out speaker- and word-dependent random effects.

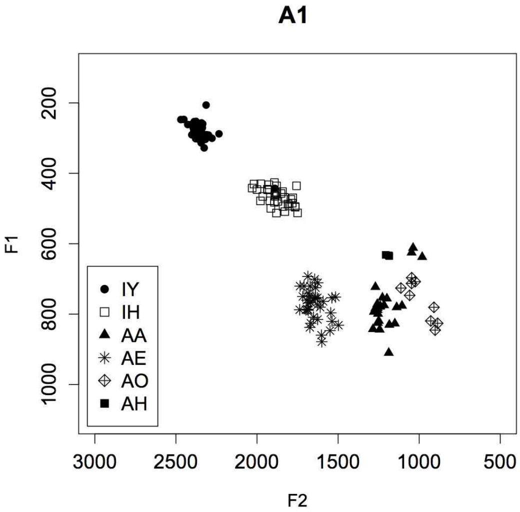
3. Results

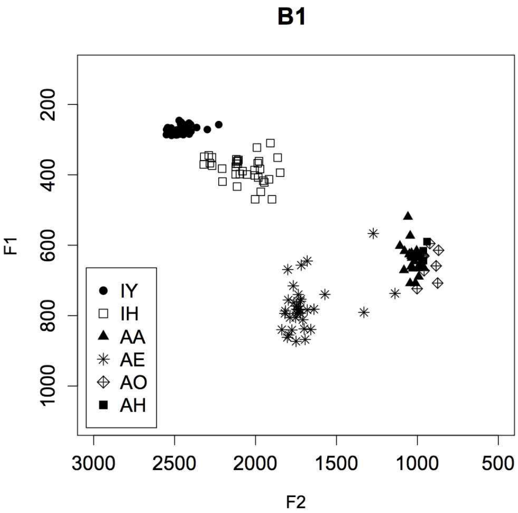
3.1. Vowel formant analysis

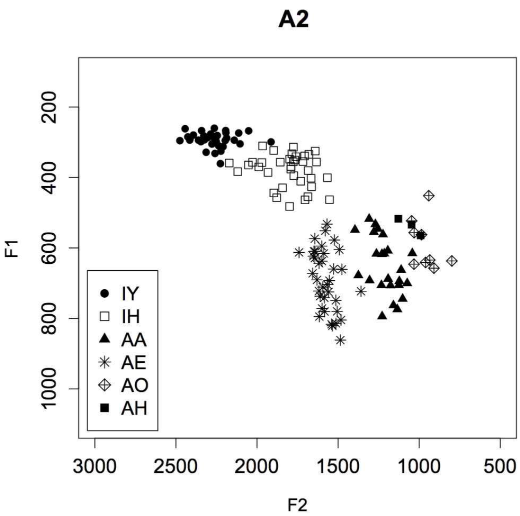
Prior to examining vowel duration, it is important to first examine what kind of vowels are produced by each speaker because our speech materials included several vowels that are known to show regional variation. In addition to auditory judgment, it would add more accuracy in the judgment of vowel quality. In this section, vowel space consisting of F1 and F2 is presented for each speaker. Formant data were collected automatically using Praat scripts (Lennes, 2003), and some tracking errors were corrected manually. The vowel space plots with F1 and F2 (Figure 2) were drawn by using an R package *vowels* (Kendall & Thomas, 2014).











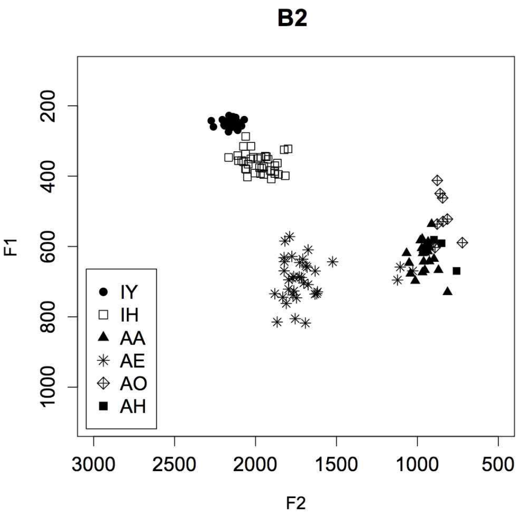


Figure 2. Vowel space for different regions of speakers: New Zealand, UK, and US. The symbols represent vowels (IY=[i:], IH=[ɪ], AA=[ɑ] or [ɒ] (depending on dialect), AE=[æ] (depending on dialect/speaker it can be [ɑ] (half, ass), AO=[ɔ:], AH=[ʌ] or [ɒ] (the vowel in of, depending on dialect)).

Figure 2 illustrates vowel space for each speaker (monophthongs only). N3 shows a low and narrow range of F1 (200~650Hz). As mentioned in Section 1.2, vowels in NZ English tend to be raised, so 'narrow mouth' is one of the characteristics in NZ English. The F1 values of N3 appear to reflect such characteristics. N3's low F2 values for [ɪ] suggests this vowel is centralized, which is another characteristic of NZ English. However, in the pronunciation of *half* and *ass*, N3 is similar to American speakers (A1, A2), producing the vowel in h*a*lf and *a*ss as [æ].

Speakers N1, N2, B1, and B2 produced the vowel in h*a*lf as a back vowel [ɑ:], rather than [æ]. In these speakers, the vowel AE symbols ('*') in the lower F2 ranges are actually [ɑ] (for example, in N2 three AE symbols appear in the F2 values lower than 1500). As for *ass*, only N1 produced the vowel in *a*ss as [ɑ], and all others produced it as [æ].

As the formant charts indicate, the vowel in *half* was short [æ] in all American speakers (A1, A2) and one NZ speaker (N3). It was [ɑː] in all British speakers (B1, B2) and two NZ speakers (N1, N2). The split between American and British was expected, but NZ speakers showed individual variation. Thus, the *half-have* pair is not a phonetically minimal pair for the latter group since it differs in not only coda voicing but also vowel quality. For the *ass-as* pair, variability was weaker –only N1 read *ass* with [ɑː] vowel, all others with [æ] vowel.

3.2. Analysis of vowel duration

As expected, in all speakers vowels before voiceless codas were shorter than vowels before voiced codas. The ratio of vowels in voiceless vs. voiced contexts is also found to be in the same range reported in the previous literature for UK and US speakers. Table 2 shows the mean duration and standard deviation for the three regions. Overall vowel durations and vowel durations before voiceless and voiced codas are shown, and their ratios are shown in the last column. The mean duration is overall the highest in US speakers, followed by UK and NZ speakers. The ratio is the highest in UK speakers (0.76), followed by US speakers (0.70), and the lowest is NZ speakers (0.59).

Table 2. Vowel duration (mean and standard deviation) and duration ratio (voiceless codas to voiced codas) by region

	All	(a) Voiceless	(b) Voiced	(a)/(b)
American	231 (66)	191 (40)	272 (62)	0.70
British	183 (56)	159 (41)	209 (58)	0.76
New Zealand	173 (77)	128 (41)	218 (78)	0.59

Figure 3 shows the duration distribution of vowels before voiced (light gray) and voiceless (dark gray) codas for each speaker. It is clear that for all speakers vowels before voiced codas are much longer than those before voiceless codas, as expected. Overall vowel duration tends to be shorter in British speakers (B1, B2) than in American speakers (A1, A2). NZ speakers have the shortest vowels before voiceless codas, with vowels before voiced codas highly variable. For N1, durations of vowels before voiced codas are similar to British speakers, especially B1. For N2 and N3, vowels before voiced codas are highly variable.

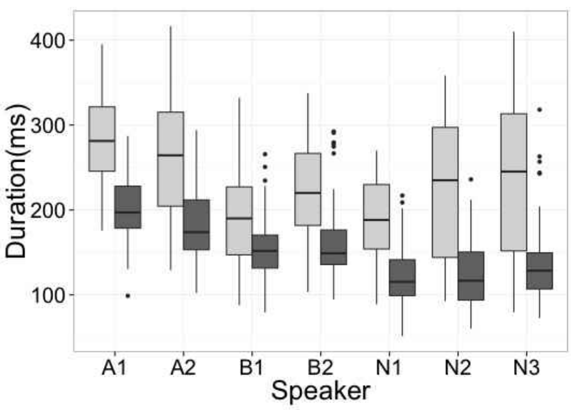


Figure 3. Vowel duration for each speaker by region. Light gray bars are vowels before voiced coda, dark gray bars are those before voiceless coda. The line in each box is median, the boxes show the first to third quartile, the whiskers show the maximum and minimum values.

Overall, there is more variation in vowel duration before voiced codas than in those before voiceless codas. This is not surprising given that there is a temporal limit in shortening whereas lengthening imposes less limit. In particular, New Zealand speakers have similar duration values for vowels before voiceless codas, whereas there is a wide range of variation in the duration of vowels before voiced codas. The New Zealanders showed the shortest vowel durations before voiceless codas among all the speakers – i.e., pre-fortis clipping is most radical in New Zealand speakers.

Linear mixed-effects regression models (Pinheiro & Bates, 2000; Baayen, 2008; Baayen *et al.*, 2008) were fitted to the data in order to figure out contribution and significance of factors determining vowel duration. The dependent variable was vowel duration, and tested predictors were coda voicing (voiceless, voiced), vowel height (high, non-high), phonemic vowel length (long, short), manner (stop, fricative, affricate), and region (NZ, UK, US). The region factor was added at the end in order to factor out the effects of other predictors first. Speakers and items (words) were treated as random effects. The best-fitting model is determined by comparing different models using maximum likelihood estimation. All the predictors significantly improve goodness of fit: voicing ($\chi^2(1)=24.93$, $p<0.0001$), vowel height ($\chi^2(1)=5.37$, $p<0.05$), manner ($\chi^2(2)=16.28$, $p<0.001$), region ($\chi^2(2)=11.75$, $p<0.01$), and phonemic vowel length ($\chi^2(1)=29.51$, $p<0.0001$).

The coefficient values of the best fitting model are reported in Table 3. The coefficients were obtained by restricted maximum likelihood estimation (Baayen *et al.*, 2008: 394). The same statistical tests were also conducted excluding *half-have* pairs (those uttered with varying [æ/ɑ] vowels) and *ass-as* pairs (of N1). The results were qualitatively the same, only the coefficients were slightly different. Thus, only the results including these pairs are reported here.

Table 3. Factors affecting vowel duration. Coefficients of the best-fitting model

	Coefficient	St.Error	t	p
Intercept	196	15	12.7	<0.0001
Voicing (voiceless)	-78	8	-9.2	<0.0001
Vowel height (nonHigh)	45	9	5.1	<0.0001
Phonemic vowel length (short)	-41	7	-5.9	<0.0001
Manner (fricative)	49	13	3.8	<0.001
Manner (stop)	11	12	0.9	0.38 (n.s.)
Region (UK)	10	14	0.7	0.46 (n.s.)
Region (US)	58	14	4.2	<0.0001

According to Table 3, vowel duration decreases by 78 ms when the coda is voiceless. Duration increases for non-high vowels by 45 ms, as one might expect. Vowel is longer before a fricative coda than an affricate coda by 49 ms and longer before a stop coda than an affricate coda by 11 ms but the latter is not significantly different from zero. Duration decreases by 41 ms for phonemically short vowels. Vowels of UK speakers are longer than those of NZ speakers by 10 ms but this difference is not significantly different from zero. Vowels of US speakers are longer than those of NZ speakers by 58 ms and this is significantly different from zero. UK and US speakers are different from each other ($p<0.05$)[3].

To sum up, the effect of PFC has observed in all speakers from three regions – vowels are shorter before voiceless codas than before voiced codas. As for overall vowel duration, NZ speakers are not significantly different from UK speakers, while both are significantly different from US speakers. American speakers have significantly longer vowels than NZ and UK speakers. Vowels are longer before fricatives than affricates and stops, high vowels are shorter than non-high vowels, and phonemically short vowels are shorter than phonemically long vowels. The ratio of vowels in different voicing contexts is the subject of the next section.

3.3. Analysis of vowel duration ratio

The results indicate that New Zealand speakers have the lowest ratios of vowels before voiceless codas to vowels before voiced codas. Figure 4 shows the ratios of the vowel durations before voiceless vs. voiced codas for each speaker. British speakers have the highest ratios, American speakers have lower ratios than British speakers, and New Zealand speakers have the lowest ratios. British speaker B1 has the highest ratio of vowel durations. New Zealand speakers N2 and N3 have the lowest ratio despite large variation.

Utterances of the *half-have* pair were excluded for speakers who have different vowels in this pair (N1, N2, B1, B2) (1.6% of total utterances) in the analysis of ratios as well as in Figure 4, because for ratio analyses, vowels need to be controlled across voicing conditions (with the pair, the results were not qualitatively different). Thus in Figure 4, data points with the ratios over 1 are true outliers, whose vowels are the same. They are: *cap-cab* (1.02), *cots-cods* (1.03), and *pads-pats* (1.00) by B1, *half-have* (1.08) by N3. PFC did not seem to occur in these pairs (2 % of total pairs).

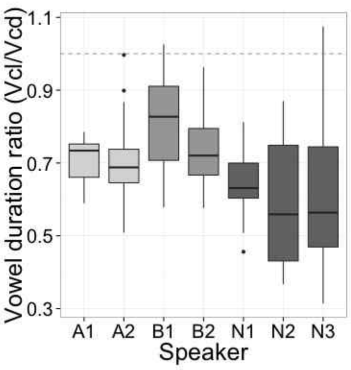


Figure 4. Vowel duration ratio (voiceless/voiced) for each speaker. The horizontal dashed line is where the ratio = 1.0, where vowel duration is the same before voiceless and voiced codas.

For the same reason, utterances of the *ass-as* pair were excluded in N1, and utterances of the *off-of* pair were excluded in A1, A2. Diphthongs were excluded in the statistical analysis because diphthongs have no vowel height value, which hinders accurate assessment of the contribution of high and non-high vowels separately.

Mixed effects linear regression models were fitted to assess significance of factors that affect PFC ratio. Dependent variable was ratio, and predictors tested were phonemic vowel length, region, vowel height, and manner. It turns out that only speaker region and phonemic vowel length were significant predictors [region ($\chi^2(2)=12.92$, $p<0.01$), phonemic vowel length ($\chi^2(1)=13.31$, $p<0.001$), vowel height ($\chi^2(1)=0.13$, $p=0.72$), manner ($\chi^2(2)=1.69$, $p=0.43$)].

Table 4. Factors affecting PFC vowel duration ratio. Coefficients of the best-fitting model

	Coefficient	St.Error	t	p
Intercept	0.53	0.028	19.2	<0.0001
Region (UK)	0.15	0.025	6.3	<0.0001
Region (US)	0.09	0.025	3.6	<0.001
Phonemic vowel length (Short)	0.12	0.032	3.6	<0.001
Vowel height (NonHigh)	0.01	0.030	0.4	0.72 (n.s.)

Table 4 shows the coefficients of the best fitting model. PFC ratio was significantly greater for phonemically short vowels than for phonemically long vowels by 0.12. This is natural given that there is physically less time for clipping in phonemically short vowels than for long vowels. PFC ratio is significantly higher in British and American speakers than in NZ speakers (0.15, 0.09, respectively). However, the ratios between UK and US were not significantly different from each other – the coefficients were not significantly different from each other ($t(92)=1.69$, $p=0.09$). The lowest ratios in NZ speakers are a consequence of their radical shortening of vowels before voiceless codas that we have seen in Figure 3.

3.4 Analyses of closure duration

It has been known that vowel duration is inversely correlated with closure duration in English (Keating, 1985; Fowler, 1991). Closure duration is generally shorter in voiceless than voiced consonants (Luce & Charles-Luce, 1985), just as opposite to vowel duration (longer for voiced consonants). In other words, closure duration is shorter under the condition where vowel duration is longer. Thus one can expect an inverse relationship between vowel duration and closure duration. Furthermore, the degree to which the two are correlated may differ in different dialects. In this section, we will examine whether and how closure duration is related to vowel duration in each dialect. In the analysis of closure duration, words with fricative codas are excluded because fricatives do not have complete closure, and only duration of frication exists.

3 A reviewer pointed out that we cannot say that the longest vowel is a characteristic of American English, because vowel duration is a reflect of speech rate, especially when they are not embedded in a carrier phrase. I agree that the results regarding the absolute vowel duration cannot be generalized as a characteristic of American English, but should be limited to the subjects recorded here. The reviewer added that speech rate must be a fixed factor. In many recording experiments, it is common to have speakers speak at self-selected speech rate. Speech may become unnatural if we force speakers to speak at exactly the same speech rate. Speakers in the present experiment were all asked to read naturally, so speech rate cannot be a categorical variable (such as slow, normal, fast). If speech rate is a numerical variable (e.g. an inverse of actual vowel duration), it would be redundant because it would be closely correlated with vowel duration.

3.4.1. Closure duration

As Figure 5 shows, closure duration is shorter in voiced consonants than in voiceless consonants in all speakers, as expected. Overall, closure duration is greatest in two NZ speakers, and UK and US speakers are similar to each other.

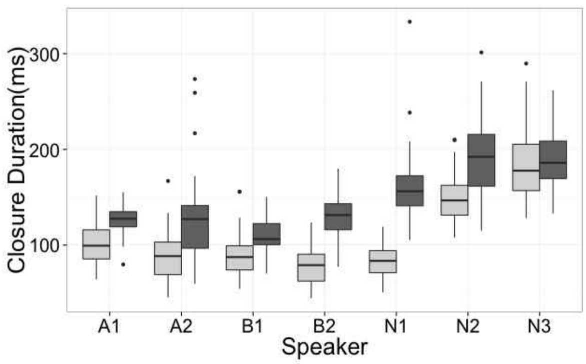


Figure 5. Closure duration for each speaker. Light gray bars represent voiced codas, and dark gray bars represent voiceless codas.

Linear mixed effects linear regression models were fitted to the data to test significance of predictors to closure duration. Dependent variable was closure duration, and predictors were the same as in the analysis of vowel duration. Random effects of speakers and items were included. Whereas all the predictors were significant in the vowel duration analysis, it turns out that only voicing and region significantly affected closure duration: voicing ($\chi 2(1)=33.67$, $p<0.0001$), region ($\chi 2(2)=8.06$, $p<0.05$), vowel height ($\chi 2(1)=1.19$, $p=0.28$), manner ($\chi 2(1)=0.20$, $p=0.65$), phonemic vowel length ($\chi 2(1)=0.09$, $p=0.76$). To this model, vowel duration was added as a predictor in order to examine the inverse relationship between vowel duration and consonant closure duration. Vowel duration significantly improved the goodness of fit ($\chi 2(1)=13.51$, $p<0.001$).

Table 5 shows the coefficients of the best model including vowel duration factor. Closure duration is longer in voiceless stops and affricates than in voiced ones by 37 ms. It is shorter in UK speakers (by 58 ms) and US speakers (by 49 ms) than NZ speakers. That is, NZ speakers have the longest closure duration. It is interesting that the dialect that has the longest closure duration shows the shortest vowel duration. Closure durations of UK and US speakers are not significantly different each other ($t(383)=-0.286$, $p=0.78$). The effect of vowel duration was very small (only –0.1 ms), but significantly different from zero ($p<0.001$). The negative value of vowel duration coefficient suggests an inverse relationship between vowel duration and closure duration.

Table 5. Factors affecting closure duration. Coefficients of the best-fitting model

	Coefficient	St.Error	t	p
Intercept	144	14	10.0	<0.0001
Voicing (voiceless)	37	5	7.7	<0.0001
Region (UK)	-58	22	-2.7	<0.01
Region (US)	-49	22	-2.3	<0.05
Vowel duration	-0.1	0.03	-3.7	<0.001

Figure 6 shows the plots of closure duration against vowel duration for each region. They are inversely correlated, as expected, though the degree of correlation is different in different accents. The correlation coefficient is the highest in UK (-0.47, $r^2=0.22$, $p<0.0001$), and US (-0.43, $r^2=0.18$, $p<0.0001$), and the lowest in NZ (-0.28, $r^2=0.08$, $p<0.0001$). Overall, the correlation coefficient is –0.39 ($r^2=0.15$, $p<0.0001$), so though not strongly, there is an inverse relation between vowel duration and closure duration.

In NZ, the vowels before voiceless codas (black points in Figure 6) stay under 200 ms, while their closure durations vary more – as a result, the correlation between vowel duration and closure duration becomes weaker. In other words the weak correlation in NZ is again due to the highest degree of vowel shortening in their dialect. On the other hand, in UK, vowel durations before voiceless codas (black points) appear more along the regression line, which yields higher correlation between vowel and closure durations.

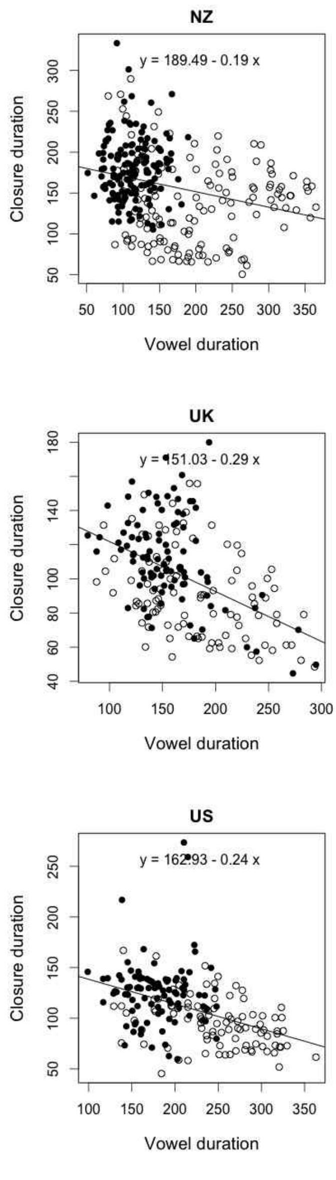


Figure 6. Scatter plots for closure duration against vowel duration. White circles are voiced codas; black circles are voiceless codas. Each panel shows a regression line with a regression equation.

3.4.2. Closure duration ratio

Figure 7 shows ratio of closure duration for voiceless vs. voiced consonants for each speaker (voiceless to voiced). There does not seem to be clear regional differences: B1 and N1 have high ratios, and other are lower.

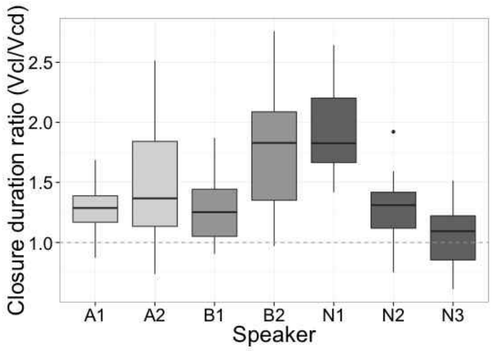


Figure 7. Closure duration ratio (voiceless/voiced) for each speaker by region. The horizontal dashed line is where the ratio = 1.0, where closure durations are the same for voiceless and voiced consonants.

Linear mixed-effects regression analyses were conducted to determine contribution of the predictors. Only manner significantly affected closure duration ratio: manner ($\chi^2(1)$=13.34, p<0.001), region ($\chi^2(2)$=0.21, p=0.90), phonemic vowel length ($\chi^2(1)$=0.19, p=0.66), vowel height ($\chi^2(1)$=2.53, p=0.11).

Table 6. Factors affecting closure duration ratio. Coefficients of the best-fitting model

	Coefficient	St.Error	t	p
Intercept	1.09	0.15	7.7	<0.0001
Manner (stop)	0.47	0.11	4.4	<0.0001

Table 6 shows the coefficients of the best fitting model. Intercept is 1.09, suggesting that closure duration is longer for voiceless than for voiced consonants. If the coda consonant is a stop, closure duration ratio increases by 0.47 than it is an affricate. In other words, the difference in closure duration between voiced and voiceless is greater when the consonant is a stop. However, unlike vowel duration and ratio of vowel durations, closure duration ratio is not dependent on speaker region.

To summarize, closure duration is longer for voiced than voiceless stops/affricates, as expected. NZ speakers show the longest closure duration, whereas US and UK speakers do not show differences each other. An inverse relationship between closure duration and vowel duration was found in all varieties. The ratio of closure durations for voiceless vs. voiced does not vary depending on variety, unlike vowel duration ratio.

4. Discussion and conclusion

In this paper, vowel shortening before voiceless consonant has been examined in three varieties of English: British, American, and New Zealand English. Vowel duration mean was the longest in American English speakers and the shortest in NZ English speakers. British and New Zealand speakers did not show a significant difference according to the linear mixed-effects linear regression analysis.

The ratio of vowel durations before voiceless and voiced codas was 0.70 in American English, 0.76 in British English, which are in the same range as the previous literature has reported. The ratio is shortest, 0.59, in New Zealand English. NZ speakers have particularly short vowels before voiceless codas while vowels before voiced codas vary. The vowel duration ratios of American and British English are not significantly different each other, but two varieties are significantly different from New Zealand English. An important finding of this paper is that NZ speakers have the most radical vowel shortening and that the ratio of vowel durations can be not only language-specific, but also dialect-specific, though the number of speakers is limited to generalize this finding.

Furthermore, closure duration was examined in three English varieties. As expected, closure duration was longer in voiceless codas than in voiced codas in all varieties. While vowel duration was the shortest in New Zealand English, the mean of closure duration was the longest in NZ English. Overall vowel duration is inversely correlated with closure duration, though weakly. Closure duration was least affected by vowel duration in New Zealand English (the smallest slope of regression line). However, the ratio of closure duration between voiceless and voiced consonants did not vary depending on accent. This suggests that in the sense of Keating (1985), vowel duration ratio is governed by a language-specific rule in New Zealand English (extreme vowel shortening), but closure duration ratio may follow a universal phonetic rule.

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