Gradient Reduction of C_1 in /pk/ Sequences*

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ABSTRACT

Instrumental studies (e.g., aerodynamic, EPG, and EMMA) have shown that the first of two stops in sequence can be articulatorily reduced in time and space sometimes; either gradient or categorical. The current EMMA study aims to examine possible factors___linguistic (e.g., speech rate, word boundary, and prosodic boundary) and paralinguistic (e.g., natural context and repetition)___to induce gradient reduction of C_1 in /pk/ cluster sequences. EMMA data are collected from five Seoul-Korean speakers. The results show that gradient reduction of lip aperture seldom occurs, being quite restricted both in speaker frequency and in token frequency. The results also suggest that the place assimilation is not a lexical process, implying that speakers have not fully developed this process to be phonologized in the abstract level.

Keywords: place assimilation, gradient reduction, categorical reduction, phonetic variability, Korean

I. Introduction

Optional place assimilation in Korean between two sequential stops (C_1C_2) in intervocalic position is traditionally viewed as categorical change of a place feature (Chomsky and Halle, 1968; Kim-Renaud, 1974) or the delinking-reassociation of place features (Clements, 1985; Cho, 1990). Experimental evidence for this kind of categorical assimilation is available from Spanish. Honorof (1999) conducted an articulatory study and demonstrated that in Spanish, /n#p/ to [mp] is true categorical place assimilation where the deleted tongue tip gesture is replaced by the lip closure gesture in time (e.g., 'digan "paja" alto' → [digampaxa], 'say (form. pl.) "straw" loudly'). However, in aerodynamic studies (Jun, 1995, 1996; Silverman and Jun, 1994), /p/ assimilated to the following /k/ involved articulatorily gradient reduction. In Jun's (1995, 1996) studies, he measured oral pressure and airflow via a mouth tube connected to an oral pressure transducer. In interpreting the oral pressure data, the amplitude of air pressure change was measured to estimate gestural magnitude of /p/ in /ipku/ and /ipk^{w}a/ sequences and gestural overlap between /p/ and /k/. Among a total of 330 tokens 47% of the tokens were categorized as reduced, where labials were deleted in all the tokens with one exception (gradiently reduced). Gradient reduction was only observed in a labial-dorsal-glide sequence /pk^w/, not occurring in /ipku/ sequences. By hypothesis, gestural magnitude of a coda segment was

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understood as being on a continuum of gestural reduction. That is, complete reduction (i.e., deletion) of a coda gesture is regarded as one extreme of the continuum, and the emergence of a coda gesture without reduction is considered as the other extreme. Partial gestural reduction can lie anywhere between these extremes. Based on the results from his production studies, he further elaborated the impact of gradient reduction during speakers' production on listeners' perception in the framework of Optimality Theory (Prince and Smolensky, 1993; McCarthy and Prince, 1995).

The articulation of consonant clusters from other languages such as English, French, German, Georgian, and Russian has been also considered in the context of variability (Chitoran et al., 2002; Ellis and Hardcastle, 2002; Fowler and Housum, 1987; Goldstein et al., 2007; Jaeger and Hoole, 2007; Kühnert and Hoole, 2004; Kühnert et al., 2006; Nolan, 1992; Zsiga, 1994, 1995, 2000). Gestural reduction and overlap have been hypothesized to be a factor to induce phonetic variability, which is observed in allophonic variation in casual speech (e.g., coronal reduction in English (Barry, 1985 from Nolan, 1992; Browman and Goldstein, 1992)). Using various methodologies, coronals have been examined in terms of reducton frequencies in American English, British English, and German (Ellis and Hardcastle, 2002; Jaeger and Hoole, 2007; Kühnert and Hoole, 2004; Kühnert et al., 2006; Nolan, 1992; Zsiga, 1994, 1995, 2000). For example, in electropalatography (EPG) studies in Barry (1985 from Nolan, 1992), the results of coronal reduction from British-English data have revealed that about one third of tokens (30.2%) were categorized as gradiently reduced tokens. However, frequent reduction was not observed using different methodologies (Ellis and Hardcastle, 2002; Jun, 1995, 1996). For a coronal nasal in /nk/ sequences of British English, only few gradiently reduced tokens were attained with inter-speaker variation in a simultaneous EPG/EMMA study on British English.

Although various instrumental phonetic studies on different languages have uncovered gradient and categorical reduction in production (e.g., its nature, frequency, perceptual aspects, rate-dependency, and so forth), the elicitation of gradient reduction in labials for Korean was not always successful. Using EMMA (Perkell et al., 1992), gestural movement of the lips and the tongue, on which transducers are attached at roughly equal distances (the tongue tip, anterior tongue body, posterior tongue body, and tongue dorsum), was physically measured (Son, 2004; Son et al., 2007). In both magnetometry studies labials in /pk/ sequences were categorically reduced, without evidence of gradient reduction being observed. In Son et al. (2007), a total of 133 tokens were available for analysis and 30.8% of the tokens were categorically reduced. This categorical labial reduction was always realized as one accentual phrase and the process was optional in this prosodic domain, having a tendency to occur more frequently at fast speech rate. This result confirmed the reduction frequency found in Jun (1995, 1996)—pooled across data, there was categorical reduction of labials with great inter-subject variability (18% of all /pk/ tokens; 36% of word-internal /pk/ tokens). Unlike Jun's (1995, 1996) data, labial reduction, however, was confined to occur in word-internal clusters. Responding to a reviewer's concern that hyperspeech might have occurred when speakers had produced presented materials in the EMMA experiments, Son et al. (2007) excluded this possibility by indicating that categorical reduction should not have occurred if the lack of gradient reduction were attributed to hyperspeech (cf., Lindblom, 1990).

For this reason, it is of importance to know why the results from the aerodynamic studies (Jun, 1995, 1996) and the EMMA studies (Son, 2004; Son et al., 2007) are different only in terms of gradient gestural reduction. One possible reason for the differences might be the different elicitation methods between Jun's (1995, 1996) and Son et al.'s (2007) studies; the latter used a less natural elicitation method, where target words were embedded in a carrier phrase (cf., unusual contexts in Bolinger, 1981 from Fowler and Housum, 1987).

Note though that it is not an uncommon practice to use a short sentence to elicit speakers' production—gradient reduction data was successfully acquired in American English (Browman and Goldstein, 1995). However, it is possible that the stimuli for Son et al. (2007) were not as natural as Jun's (1995, 1996) study which used materials presented in natural sentences composed of three to seven words. Thus, in our current production study we replicate Son et al.'s (2007) experiment using materials presented in paragraphs.

Another possible reason that Son et al. (2007) failed to acquire gradient reduction could be because every target syllable (VC_1), with both heterorganic and homorganic clusters, consistently appeared in the initial position of a phrase (e.g., accentual phrase and intonational phrase: Jun (1993)). This prosodic condition could have suppressed token-to-token variability in gradient reduction. Thus, the lack of gradient reduction in production could have been due to the failure of gradient reduction to occur in this position, rather than non-existence of such a phenomenon altogether. In an effort to elicit token-to-token variability in coda position, both prosodic phrase initial and final position were strictly avoided.

In addition to using natural sentences which are configured to elicit more token-to-token variability in reduction, a repetition method is employed that has been claimed to elicit productions with reduced articulatory effort. In an acoustic study of running speech cropped from a contemporary radio program, Fowler and Housum (1987) showed that repetition resulted in shrinkage in duration and amplitude for a word repeated within a paragraph (average of three words apart between new and old words). It is plausible that the shrinkage observed in old words is caused by more gestural overlap between two segments (e.g., /pk/ clusters) and more gestural reduction in space and time. In our stimuli set, new words refer to the first four times a word is produced in reading. Old words refer to the second four times a word is produced in reading.

2. Experiment and data analysis

2.1 Participants and Materials

For our production experiment, a total of seven subjects were employed, five female and two male, but data from two female speakers were not available for analysis due to either the chronic failure of transducer coils for tongue dorsum movement or signal processing problems. Data from five subjects (three females (K1, K3, and K4) and two males (K2 and K5)) were used in the analysis. All subjects, none with any speech impairment, were naïve to the purpose of the experiment. They all identified themselves as speaking Seoul-Korean dialect. Speakers were at age thirty-one on average—twenty-seven years in Seoul, Korea and four years abroad. They were residing in U.S.A. for their graduate studies or post-doctoral research at the time of the experiment.

/pk/ clusters, which is known to be an assimilation context, were collected along with control /pp/ and /kk/ clusters. The three different cluster types appeared in natural contexts presented in a paragraph form. Two different speech rates (either fast or comfortable) and different word boundary conditions (within-word and across-word conditions) were employed. The stimuli were presented in random order, but the order of stimuli within a block of presentation remained the same across speakers. Target syllables with C_1 appeared neither word initially nor word finally—nor did control syllables. Each target/control word/phrase was repeated four times in the paragraph. All speakers were asked to read a presented paragraph on a computer screen two times in a row, abiding by the required speech rate. The rate and word boundary conditions were blocked and elicited in the same order for each subject___phrase comfortable, phrase fast, word comfortable, and word fast. A total of thirty-two repetitions of each target word/phrase were rendered. The larger sentential context in which these occurred could be consistent or varied within a paragraph; a priority of contextual variation was given to natural meaning of sentences. In (1), the transliteration of target words or word pairs is shown along with its phonetic transcription and gloss. The whole stimuli set is shown in the endnote[i].

(1) Stimuli list for EMMA experiment

(a) Within-word boundary condition

Transliteration	*Phonetic transcription*	*Gloss*
(i) control /pp/		
/jʌn-hap-pan/	[jənha**pp**an]	‘joint class (연합반)’
(ii) control /kk/		
/a-ak-ka/	[aa**kk**a]	‘traditional royal musical song (아악가)’
(iii) /pk/ cluster		
/ʧʌ-ap-ka/	[ʧə**apka**] or [ʧə**akka**]	‘low pressure value (전압가)’

(b) Across-word boundary condition

Transliteration	*Phonetic transcription*	*Gloss*
(i) control /p#p/		
/nan-hap # pat-a/	[nanha**pp**ata]	‘getting a small bowl coming with a lid (난합 받아)’
(ii) control /k#k/		
/ʧʌn-hak # ka-taka/	[ʧənha**kk**ataka]	‘on the way of transferring schools (전학 가다가)’
(iii) /p#k/ cluster		
/nan-hap # kaʧi-ko/	[nanha**pka**ʧiko] or [nanha**kka**ʧiko]	

'having a small bowl with a lid and (난합 가지고)'

2.2 Method and Measurements

The Perkell-system electromagnetic midsagittal articulometer system (EMMA) at Haskins Laboratories was used to collect kinematic data of the lips and the tongue. Two transducers were attached on the upper lip and lower lip, and four transducers on the tongue__the tongue tip, anterior tongue body, posterior tongue body, and tongue dorsum__at roughly equal distances. They were aligned with each subject's vocal tract in the midsagittal plane.

Oral gestures are defined by constriction variables (i.e. degree and location). For this study, spatial and temporal properties of gestures are measured with respect to the constriction degree of the lips (LA) and tongue dorsum (TD). These are estimated using a Matlab-based procedure, MVIEW (Tiede, 2005). For measurements of lip gesture, lip aperture is measured as the Euclidean distance between the transducers on the upper and lower lips. For measurements of a dorsal segment, the vertical movement of the tongue dorsum is measured, since mere vertical movement seems more accurate due to uncertainty about position of the soft palate.

To find the maximally constricted values for lip aperture (during /p/) and to find the highest position of the tongue dorsum (during /k/), a function (Snapex) was employed that finds the nearest position extremum (velocity zero) to the time location at which the user clicks. To find the times of gestural onset, target attainment, and release a second function (Findgest) was employed. The gestural onset was defined when the velocity of the corresponding constrictor exceeded a threshold, defined as a percent of the difference between the local speed minimum and speed maximum. Time of target attainment and release were measured in similar ways; constrictional threshold values for each constrictor and for each speaker are determined after going over sample tokens chosen at random. In analyzing data, a 40% of threshold is used for lip aperture and a 30% for the tongue dorsum.

Using measurements of gestural landmarks, gestural reduction is defined using the minimum values of constriction degree for lip aperture and extreme maximum values of vertical movement for the tongue dorsum, as discussed above. Temporal constriction interval is defined as temporal duration from the target attainment to the release of C_1 (i.e., constriction duration).

Tokens in which both algorithm fail to find any constriction event in the relevant temporal region are considered to be instances of complete gestural reduction (i.e., deletion). For these tokens, the "constriction" value for C_1 is measured at the target attainment of C_2 (see Son et al., 2007). For control /kk/ sequences, the constriction value for lip aperture was measured at the target attainment of the tongue dorsum gesture. For /pk/ clusters with categorical reduction (deletion) of lip aperture, the same time series were taken and compared to the values of lip aperture for control /kk/ clusters. For control /pp/ sequences, the constriction value for the tongue dorsum gesture was measured at the target attainment of lip aperture in order to compare it to the /pk/ clusters with a categorically reduced tongue dorsum gesture. One token was eliminated from a further analysis due to mispronunciations.

3. Results

3.1 Constriction Degree of Lip Aperture as C_1

As for the constriction degree of lip aperture in /pk/, an analysis of variance was conducted, including Subject (five speakers), Boundary (across-word and within-word), Rate (fast and comfortable rate of speech), and Repetition (first four times a word is produced in reading vs. second four times). In the overall analysis pooling across all subjects in Table 1, there was a main effect of Subject, a main effect of Boundary, and a main effect of Rate at the significance level of .05. The results showed significant interactions between Subject and Boundary, and between Subject and Rate.

Table 1. A summary of significant main effects of the constriction degree of /p/ as C_1 in /pk/ across subjects.

Main effects	Across subjects	Interactions	Across subjects
Subject	F (4, 159) = 279.27*	Subject and Boundary	F (4, 159) = 17.09*
Boundary	F (1, 159) = 5.63*	Subject and Rate	F (4, 159) = 3.43*
Rate	F (1, 159) = 32.60*		
Repetition	Not significant		

(* $p < .05$)

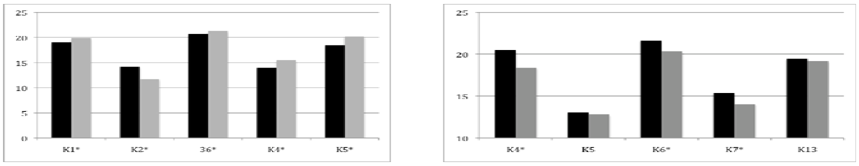
Since Subject interacted with Boundary and with Rate, an analysis of variance was conducted separately for each speaker and included three factors: Boundary, Rate, and Repetition. We show the results of a factorial analysis of variance by subject, including the F-values of significant main effects in Table 2 ($p < .05$). There was a main effect of Boundary for all subjects, a main effect of Rate for three subjects (K1, K3, and K4), and a main effect of Repetition for one subject (K1).

Table 2. A summary of significant main effects of the constriction degree of /p/ as C_1 in /pk/ by subject.

Subject	K1	K2	K3	K4	K5
Boundary	F (1, 32) = 15.67*	F (1, 32) = 9.45*	F (1, 32) = 23.23*	F (1, 32) = 28.50*	F (1, 32) = 61.80*
Rate	F (1, 32) = 88.13*	Not sig.	F (1, 32) = 117.02*	F (1, 32) = 23.60*	Not sig.
Repetition	F (1, 32) = 6.76*	Not sig.	Not sig.	Not sig.	Not sig.

(* $p < .05$)

In Figure 1.a, the constriction degree of lip aperture for different boundary conditions is shown by subject. Most speakers (K1, K3, K4, and K5) consistently showed more constriction in the across-word condition than in the within-word condition, with one exception (K2). This speaker showed less constriction in the across-word condition. In Figure 1.b, the constriction degree of lip aperture of /p/ as C_1 in /pk/ clusters for different rate conditions is shown by subject. Three subjects (K1, K3, and K4), who had significant effects, all showed more constriction in comfortable rate in a consistent way. Two other speakers (K2 and K5) also tended to show more constriction in comfortable rate.



(a) across-word vs. within-word conditions (b) fast vs. comfortable rate

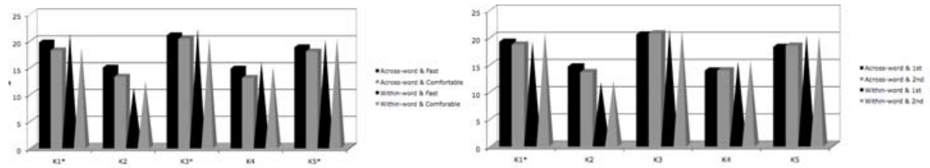
Figure 1. Means for the constriction degree of lip aperture in /pk/ clusters by subject: The x-axis represents different subjects and the y-axis the values of constriction degree in millimeters. Smaller numbers indicate more constriction. A bar in black represents the across-word condition and a bar in gray the within-word condition in Fig. 1.a. A bar in black represents fast rate and a bar in gray comfortable rate in Fig. 1.b. Statistically significant effects are indicated by an asterisk ($p < .05$).

For the effect of repetition, one speaker (K1, $p < .05$) indicated that new words were produced with a more constriction (19.14 (.15) ms) compared to old words (19.71 (.15) ms), which was predicted. For the other speakers, repetition effects were not observed.

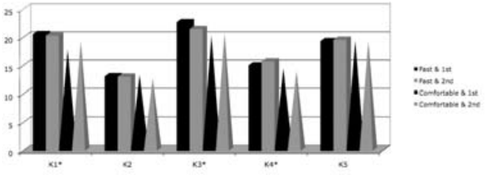
With respect to the interaction between Boundary and Rate, between Boundary and Repetition, and between Rate and Repetition, the results of five speakers are shown in Figures 2.a, 2.b, and 2.c, respectively. In Figure 2.a, less constriction was obtained in fast rate consistently in both boundary conditions for two speakers (K1 and K3). Rate effect was greater in the within-word condition (19.7 (.22) mm in the fast rate of the across-word condition vs. 18.26 (.22) mm in the comfortable rate of the across-word condition vs. 21.21 (.22) mm in the fast rate of the within-word condition vs. 18.52 (.22) mm in the comfortable rate of the within-word condition for K1; 21.05 (.11) mm in the fast rate of the across-word condition vs. 20.36 (.11) mm in the comfortable rate of the across-word condition vs. 22.18 (.11) mm in the fast rate of the within-word condition vs. 20.35 (.11) mm in comfortable rate of the within-word condition for K3). For speaker K5 the same effect of rate was also observed in the across-word condition (18.83 (.22) mm in fast rate vs. 18.05 (.22) mm in comfortable rate), while we did not obtain the same pattern in the within-word condition (20.15 (.22) mm in fast rate vs. 20.28 (.22) mm in comfortable rate).

In Figure 2.b, the results of the interaction between Boundary and Repetition showed that less constriction in old words was obtained in the within-word condition for one speaker (K1) with a significant effect (19.03 (.22) mm in new words vs. 20.7 (.22) mm in old words for K1). However, in the across-word condition, more constriction was observed in old words, which was not predicted (19.25 (.22) mm in new words vs. 18.73 (.22) mm in old words).

In Figure 2.c, the results of the interaction between Rate and Repetition showed statistical significance for three speakers with inter-speaker variation (K1, K3, and K4; $p < .05$). One speaker (K1) showed that less constriction in old words was observed exclusively in the comfortable rate condition (17.68 (.22) mm for new words vs. 19.10 (.22) mm for old words). Another speaker (K4) indicated less consrtiction in old words confined to fast rate (15.06 (.29) mm for new words vs. 15.75 (.27) mm for old words). Unlike these two speakers, one speaker (K3) did not demonstrate reduction in old words in any rate condition.



(a) Interaction between Boundary and Rate (b) Interaction between Boundary and Repetition



(c) Interaction between Rate and Repetition

Figure 2. Constriction degree of lip aperture of /p/ in /pk/ clusters. In Figure 2.a, a bar represents the across-word condition and a cone the within-word condition. Black represents fast rate and gray comfortable rate. In Figure 2.b, a bar represents the across-word condition and a cone the within-word condition. Black represents new words and gray old words. In Figure 2.c, a bar represents fast rate and a cone comfortable rate. Black represents new words and gray old words. Smaller numbers indicate more constriction for lip aperture in millimiters. Statistically significant effects are indicated by an asterisk ($p < .05$).

To sum up, there was inter-speaker variation in both main effects and interactions. For four out of five speakers with a significant boundary effect showed more constriction in the across-word condition and all three speakers who had a significant rate effect showed less constriction in fast rate, not in comfortable rate.

3.2 Gestural Constriction Duration of C_1

The constriction duration of lip aperture in C_1C_2 sequences (i.e., time intervals of gestural target to release) was examined using a factorial analysis of variance: factors included Subject (five speakers), Boundary (across-word and within-word conditions), Rate (fast and comfortable rate of speech), and Repetition (first four times a word is produced in reading vs. second four times). The results of the analysis pooling across all subjects showed a main effect of Subject, a main effect of Boundary, and a main effect of Rate. There were significant interactions between Subject and Boundary, and between Subject Rate. The F-values of significant main effects and signficant interactions for the constriction duration are shown in Table 3 ($p < .05$).

Table 3. A summary of significant main effects and significant interactions of the constriction duration across subjects.

Main effects	Across subjects	Interactions	Across subjects
Subject	F (4, 159) = 7.56*	Subject and Boundary	F (4, 159) = 4.52*
Boundary	F (1, 159) =8.03*	Subject and Rate	F (4, 159) = 4.21*
Rate	F (1, 159) =15.13*		
Repetition	Not sig.		

(* $p < .05$)

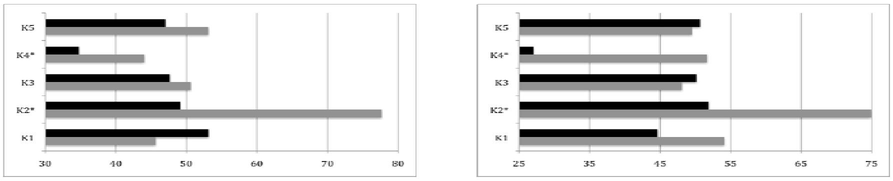
Since Subject interacted with Boundary and with Rate, an analysis of variance was conducted using three factors: Boundary, Rate, and Repetition. In Table 4, we show the F-values of significant main effects for the constriction duration of /p/ as C_1 ($p < .05$).

Table 4. A summary of significant main effects of the constriction duration of lip aperture in /pk/ clusters by subject.

	K1	K2	K3	K4	K5
Boundary	Not sig.	F (1, 32) = 26.97*	Not sig.	F (1, 31) = 5.78*	Not sig.
Rate	Not sig.	F (1, 32) = 17.65*	Not sig.	F (1, 31) = 40.78*	Not sig.
Repetition	Not sig.	Not sig.	Not sig.	Not sig.	Not sig.

(* $p < .05$)

Using bar graphs, the mean values of the constriction duration for /p/ as C_1 in different boundary conditions are shown in Figure 3.a, and those in different rate conditions in 3.b.



(a) Across-word vs. within-word conditions (b) Fast vs. comfortable conditions

Figure 3. Means for the constriction duration of lip aperture in /pk/ clusters by subject: The x-axis represents constriction duration values in milliseconds and the y-axis different subjects. Bars in black represent the constriction duration of /p/ for the across-word condition in Figure 3.a and for the fast rate condition in Figure 3.b. Bars in gray represent the constriction duration of /p/ for the within-word condition in Figure 3.a, and for the comfortable rate condition in Figure 3.b. Smaller values indicate shorter constriction duration. Statistically significant effects are indicated by an asterisk ($p < .05$).

For labial stop /p/ in /pk/ clusters, the results of two speakers (K2 and K4) reached statistical significance at the .05 level. Labial stop /p/ consistently indicated shorter constriction duration for the across-word condition than for the within-word condition (49.15 (3.87) ms vs. 77.65 (3.87) ms for K2; 34.74 (2.77) ms vs. 44 (2.66) ms for K4). Shorter constriction duration was also observed in the fast rate condition for these speakers (51.87 (3.87) ms in fast rate vs. 74.90 (3.87) ms in comfortable rate for K2; 27.08 (2.77) ms in fast rate vs. 51.66 (2.66) ms in comfortable rate for K4).

Given in Table 6 are the F-values and p-values of significant interactions for the constriction duration of /p/ as C_1. Two subjects showed a significant interaction between Boundary and Rate (K4 ($F[1, 31] = 5.99$, $p < .05$) and K5 ($F[1, 32] = 4.65$, $p < .05$)).

In Figure 4, the constriction duration of /p/ as C_1 between the two factors is shown by subject.

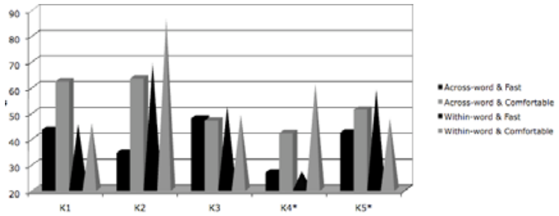


Figure 4. Constriction duration of lip aperture: Interaction between Boundary and Rate by subject. The x-axis represents different subjects and the y-axis constriction duration values in milliseconds. Bars are for the across-word condition and cones are for the within-word condition. Black represents fast rate and gray comfortable rate. Smaller values indicate shorter constriction duration. Statistically significant effects are indicated by an asterisk ($p < .05$).

Looking at the interaction between Boundary and Rate simultaneously, there was inter-speaker variation. The results of one speaker (K4) showed that the rate effect was greater in the within-word condition (27 (3.77) ms in fast rate vs. 61 (3.77) ms in comfortable rate) than in the across-word condition (27.2 (4.07) ms in fast rate vs. 42.32 (3.77) ms in comfortable rate). For K5, the results showed shorter constriction duration in the fast rate of the across-word boundary condition (42.56 (4.67) ms) in fast rate vs. 51.5 (4.67) ms in comfortable rate), but not in the within-word condition (58.75 (4.67) ms in fast rate vs. 47.50 (4.67) ms in comfortable rate).

We found that fast rate and across-word boundaries are conditions for more temporal reduction of /p/ for two speakers (K2 and K4). Regarding an interaction between Boundary and Rate, one speaker (K5) showed an aberrant pattern which revealed more temporal reduction in comfortable rate than in fast rate, although it was confined to the within-word condition.

In section 3, we showed that more spatial reduction occurred in the within-word boundary condition for most speakers except for one (K2). More spatial reduction was also consistently observed in fast rate for three speakers. Interestingly, more temporal reduction was *not* observed in the within-word boundary for any speakers. Rather, two speakers showed more temporal reduction in the across-word boundary condition. Consistent with the result of spatial reduction, more temporal reduction was observed in fast rate for two speakers. Based on the results of constriction degree and constriction duration obtained in section 3, we examine the distribution and the frequency of gradient reduction and categorical reduction in section 4.

4. Coda reduction in VC_1C_2V contexts

4.1 Token Classification

Gestural reduction has been hypothesized to occur as a function of temporal duration (cf., vowel reduction: Lindblom, 1963). In contrast, counterevidence is found in Gay (1978) where unreduced vowels can be attained despite short duration. Independent of spatial reduction, shorter closure duration is known to influence listeners’ perceptibility of stop consonants and induce assimilation (cf., voicing contrast: Pickett et al., 1995; Ohala, 1990). However, based on gradient reduction data, as we used each variable as a predictor of the other variable using linear regression, results showed that labial temporal gradient reduction did not explain a significant proportion of variance in spatial gradient reduction ($R^2 = .031$, $F(1, 21) = .646$, $p > .05$). Nor did spatial gradient reduction explain a significant proportion of variance in temporal gradient reduction (R^2 = .001, F (1, 11) = .015, p > .01). Therefore, reduction in the current study is defined based on measurements of both temporal values and spatial values of gesture, partitioning them into three different categories, e.g. two extremes on a gestural scale (full production and categorical reduction), and one occurring anywhere between the two extremes (gradient reduction). The criteria we use in order to define the three different gestural behaviors in C_1 of heterorganic C_1C_2 clusters refer to the interquartile mean and its standard deviation of the heterorganic cluster type: by definition, 16 tokens out of 32 tokens pooled across conditions (e.g., two rates X two boundaries X eight repetitions). Reduction was defined within a given cluster type (e.g., lip aperture values of /p/ in /pk/ clusters without including control /pp/) for each subject. Tokens were classified according to the procedures indicated below.

(2) Token classification

(a) C_1 of heterorganic C_1C_2 cluster sequences are unreduced if:

i) Findgest detects gestural landmarks (i.e., gesture onset, target attainment, and release) within a properly selected window, and

ii) temporal values for target-release duration are not smaller than 3 times the standard deviation of the interquartile mean of heterorganic C_1C_2 cluster sequences (cf., Kochetov and Pouplier, to appear), and

iii) spatial values for maximum constriction are not less constricted than 3 times the standard deviation of the interquartile mean of heterorganic C_1C_2 cluster sequences.

(b) C_1 of heterorganic C_1C_2 cluster sequences are gradiently reduced if:

i) Findgest detects gestural landmarks within a properly selected window, and

ii) temporal values for target-release duration are smaller than 3 times the standard deviation of the interquartile mean of heterorganic C_1C_2 cluster sequences, and

iii) spatial values for maximum constriction are less constricted than 3 times the standard deviation of the interquartile mean of heterorganic C_1C_2 cluster sequences, but more constricted than 3 times standard deviations of the interquartile mean in homorganic control utterances without the relevant constriction (in C_2C_2 control utterances, a time point of the relevant constriction of C_1 in C_1C_2 was measured at the target attainment of homorganic C_2C_2 clusters).

(c) C_1 of heterorganic C_1C_2 cluster sequences are categorically reduced if:

i) Findgest fails to detect gestural landmarks within a properly selected window, or

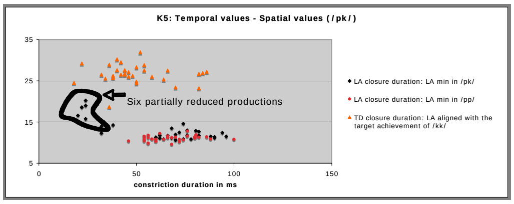
ii) temporal values for target-release duration are smaller than 3 times the standard deviation of the interquartile mean of heterorganic C_1C_2 cluster sequences, and

iii) spatial values for maximum constriction are less constricted than 3 times the standard deviation of the interquartile mean of heterorganic C_1C_2 cluster sequences, and not more constricted than 3 times standard deviations of the interquartile mean in homorganic control utterances (in C_2C_2 control utterances, a time point of the relevant constriction of C_1 in C_1C_2 was measured at the target attainment of homorganic C_2C_2 clusters).

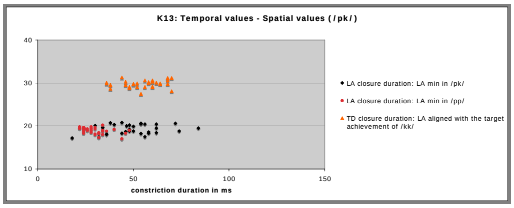
Appropriateness of the criteria can be evaluated qualitatively by looking at the graphs (see Figs. 5), which show bimodal distribution of constriction values.

4.2 Partially Reduced Tokens Identified

A total of 159 tokens of /pk/ sequences were analyzed in order to identify which tokens were reduced (five subjects X two rates X two boundaries X two information X four repetitions). In Figure 5, data for five subjects are shown using scatter plots. In each of the graphs in Figure 5, lip aperture values from three sets of tokens are plotted: /p/ in /pk/, /p/ in /pp/, and /k/ in /kk/ (for /kk/, the temporal value is not of lip aperture but tongue dorsum constriction; the temporal value of this control is not relevant to error classification; it is there just for parallelism). All speech rate, word boundary, and information conditions are pooled together for each speaker. Based on the compound criteria (see, section 4.1), tokens classified as gradient reduction constitute a distinctive distribution from unreduced and control cluster sequences as is seen in Figure 5.a for K2. There was no categorical reduction for any speakers. The other speakers showed no gradient reduction. We present the result of K5 in Figure 5.b___the graph clearly shows a bimodal distribution and nothing in between. The results of the other speakers (K1, K3, and K4) patterned with that of K5 (Fig. 5.b).



(a) Speaker K2: Six gradiently reduced tokens of /pk/



(b) Speaker K5: No gradient reduction of /pk/

Figure 5. *Distribution of gradiently reduced tokens of /pk/ cluster sequences for K2 and K5: The x-axis represents constriction duration and the y-axis constriction degree. The distinctive cluster is marked with a circle in bold.*

Only one of the speakers produced any gradient reduction of /p/: for this speaker (K2), gradient reduction of the lip aperture gesture was observed in the across-word boundary condition, having occurred in four tokens of the fast rate and two tokens of the comfortable rate.

Using the established compound criteria in section 4.1, gradient reduction also occurred in onset in two tokens. Two subjects (K2 and K4) had the tongue dorsum gesture of one /pk/ token partially reduced in fast rate. This occurred in the across-word condition for K2 and in the within-word condition for K4. However, compared to the reduction of coda in /pk/ clusters (e.g., 3.8% of the productions during /p/ across subjects), the percentage of partial reduction of onset in /pk/ clusters (e.g., 1.3% during /k/ in /pk/) are much lower.

5. Discussion

Regarding gestural reduction, it is of importance for us to find direct kinematic evidence of gestural reduction in Korean before in-depth discussion of its implication on phonological alternations. Using the criteria employed in section 4.1, only one subject shows gradient reduction of labial stops in coda, doing so in six tokens. The results show that gradient reduction of labial stops in coda is quite restricted as is consistent with data from Jun (1995, 1996). Other instances of reduction in the onset position are quite sporadic and probably reflect noise in the data.

By strictly avoiding intonational phrase boundary and accentual boundary position, and employing natural sentences, we find one speaker showing some tokens (six out of thirty-two) of gradient gestural reduction of the first of /pk/. Since using a compound measure eliminates some tokens from being counted as gradiently reduced, we examine further the distribution of data in each domain as we apply an appropriate clause of the established criteria. In three different classifications, gradient reduction of labial stop /p/ in /pk/ clusters is more common at fast rate compared to comfortable rate (5.1% vs. 2.5% using the compound criteria). This result is compatible with previous articulatory studies for languages such as English, German, Korean, and Russian (Barry, 1992; Jun, 1995, 1996; Nolan, 1992; Kühnert and Hoole, 2004; Kochetov and Goldstein, 2004). However, we do not obtain gradient reduction as a rate-dependant process (Wilcoxon signed-rank tests, $p > .05$). Looking at the results for individual speakers, there are two groups of speakers—one group produces either unreduced or gradiently reduced lip gestures and the other group produces only unreduced lip aperture. Inter-speaker assimilation differences are also attained in assimilation processes of the other languages listed above (Barry, 1992; Jun, 1995, 1996; Nolan, 1992; Kühnert and Hoole, 2004).

Regarding the grdient reduction of coda in /pk/ clusters (e.g., 3.8% of the productions during /p/ across subjects) which is compared to lower percentage of gradient reduction of onset in /pk/ clusters (e.g., 1.3% during /k/ in /pk/), it is plausible that we observe this pattern due to different ranges of standard deviations for /p/ and for /k/. Recall that we use standard deviations within a cluster type (e.g., /pk/) when it comes to defining gradient reduction. Therefore, it highly depends on how close or far data points are to the mean. When we calculate the mean of the standard deviation for temporal and spatial values[1], numerical values of coda indicate a wider distribution of /p/ in /pk/ compared to /k/ in /kp/ for one speaker (K2) who produces few gradiently reduced lip gestures (e.g., 15.49

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1) The standard deviations are calculated based on all data points within a cluster type without discriminating between different reduction types.

ms and 1.03 mm for /p/ of /pk/; 11.4 ms and 0.5 mm for /k/ of /pk/). This means that classifying a token as gradient reduction for dorsals could not require as much reduction as those of labial coda; thereby, it supports our conclusion that gradiently reduced /k/ as C_2 probably reflects noise in the data. However, not all comparisons show data points close to the means—onset /k/ in /pk/ for one speaker (K4) show that data points are as widely distributed as coda /p/ (17.94 ms and 0.96 mm).

Although there is some evidence for the postlexical status of Korean place assimilation (e.g., speaker variability and rate-relatedness (see also, Jun 1995, 1996; Kim-Renaud, 1974), Son et al. (2007) find that the Korean categorical labial reduction is true deletion, not applying in the across-word boundaries but in the across-morpheme boundaries within a prosodic word; thereby, the place assimilation rule is a lexical process (Kiparsky, 1985; Mohanan, 1993). To the contrary, in the current production experiment, we show that most speakers do not reduce the lip aperture gesture at all with one exception (K2): there are just few instances of gradient reduction confined to the across-word condition for this particular speaker. Given the results of the current study, it rather seems plausible that place assimilation occurs as a result of the undershoot of a gesture in the phonetic execution level, not being specified in the input level (Nam and Goldstein, 2007). Another piece of evidence to support its post-lexical status comes from the lack of evidence that no speaker produces categorically reduced lip aperture in /pk/ cluster sequences in 100% of his/her productions (cf., Ellis and Hardcastle, 2002).

With respect to a repetition effect (Fowler and Housum, 1987), we do not find strong evidence that old words (e.g., second four times a word is produced in reading in our study) are articulatorily reduced except for one subject (K1) who produces less extreme lip aperture in old words. The results of this particular speaker show an interaction of repetition effects with boundary and rate—within-word boundary and comfortable rate conditions. A possible reason that we seldom acquire repetition effects in our current study can be attributed to a less natural environment where the same target word is repeated. This is different from materials used in Fowler and Housum (1987) who employ spontaneous speech for analysis and reaveal repetition effects.

Note that we fail to elicit a single case of categorical reduction in the coda, although some gradiently reduced productions are attained. This is the opposite of what Son et al. (2007) obtain in their EMMA experiment in which some categorically reduced tokens are observed. Although it is not possible for us to pin down the source of different types of reduction (categorical reduction (deletion) vs. gradient reduction) between two studies, it seems plausible that the difference is related to our using target words in different contexts—we repeat a target word four times in a paragraph in our current production experiment. Due to this particular way of presenting read materials to five subjects, it is possible that the speakers may be too careful to delete a segment categorically. To the contrary, in Son et al. (2007), three subjects are asked to repeat a short sentence roughly eight times in a row where a target word is embedded—by doing this, this particular method may be related to mechanical reading by speakers, which in turn influences the emergence of categorical deletion of lip aperture. In addition to possibly different reading styles depending on different presentations of the stimuli, our current results may have something to do with different prosodic conditionings: a target segment occurs in the initial position of an accentual phrase in Son et al. (2007), but in the second syllable of an accentual phrase in the current production experiment.

In Jun's aerodynamic study (1995, 1996), he concludes that perceived assimilation is attributed to gestural reduction (either partial or gradient), not gestural overlap. However, the way he defines gestural reduction and gestural overlap in the aerodynamic study does not enable him to directly measure the degree of reduction in time and space. Neither of the time intervals between two successive gestures (e.g., intergestural lag and constriction overlap) is measured. One aspect we cannot ignore is that there can be a correlation between more reduction (in terms of constriction duration and constriction degree as C_1) and more overlap (e.g., shorter intergestural lag). With this in mind, caution should be taken before anyone makes a claim for the role of each variable in perceived place assimilation (cf., Jun, 1995, 1996; Son et al., 2007). In our future study, we will make use of synthesis (e.g., the Task Dynamics application (Nam and Goldstein, 2007)) to control speech materials in order to thoroughly investigate perceptual consequences of each variable (gestural reduction vs. gestural overlap).

Although we suspend judgment until we have better controlled perceptual data using synthesis, the trigger that initiated this change, we propose, is general principles of gestural overlap and gestural reduction, and their perceptual consequences (Browman and Goldstein, 1990, 1991, 1992; Byrd, 1992; Chen, 2003; Jun, 1995, 1996; Son et al., 2007). According to articulatory phonology (Goldstein and Fowler, 2003), gestural tasks are perceptual target to be adapted in production and in perception (see, linguistic communication as public actions between two parties (i.e., speakers and listeners). Through server mis-imitation of such gradient reduction and/or more overlap in the interaction between speakers and listeners over time (Browman and Goldstein, 1991, 2000; Chen, 2003; Goldstein and Fowler, 2003; Liberman and Whalen, 2000; Ohala, 1989, 1990, 1993), both parties could have eventually developed extreme reduction (i.e., deletion) and phonologized this (Ellis and Hardcastle, 2002; Son et al., 2007). Therefore, two variables seems to cooperatively lead to the process in the direction of total disappearance of the labial gesture in /pk/ clusters.

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[i] Whole stimuli set

Control /pp/: /hakinjʌni toiʧa, tokʌ ilʌ jʌnhappanɛ peʧʌŋ patas:ʌjo. jʌnhappanɛsʌnɨn okukʌ sikanɛ talɨn jʌnhappanɛsʌ on ʧʰinkutɨlkua suʌpɨl katʰi hes:ʌjo. jʌnhappan peʧʌŋɨlo talɨn pan ʧʰinkutɨlkuato ʧʰinheʧjʌs:ʌjo/

"When I became a sophomore, I was assigned to a joint class for German and Japanese. People from the other joint class of German and Japanese joined us for foreign language classes. Since I was assigned to the joint class, I became friends with them too."
이학년이 되자, 독어 일어 연합반에 배정 받았어요. 연합반에서는 외국어 시간에 다른 연합반에서 온 친구들과 수업을 같이 했어요. 연합반 배정으로 다른 반 친구들과도 친해졌어요.

Contro /kk/: /motu ta aakkaɨi sʌmsɛhamɛ panhako, motu ta aakkaɨi sʌnjulɛ ʧʰuihesʌ, motu ta aakkaman tɨlʌs:ʌjo. Motu ta aakkaɨi ʧʌŋkjohamɛ kamtʰanhes:ʌjo/

"Being fascinated by the sensitivity and absorbed in the melody of the Royal music, everyone listened to it exclusively. Everyone was so impressed by the subtlety of the Royal music."
모두 다 아악의 섬세함에 반하고, 모두 다 아악가의 전율에 취해서, 모두 다 아악가만 들었어요. 모두 다 아악가의 정교함에 감탄했어요.

/pk/ sequences: /mulihak pokosʌ ʧaksʌŋsi, ʧʌapkanɨn kiponɨlo pʰjosihejo. ʧʌapkanɨn suɨnʧulɨl pomjʌn al su is:nɨntɛ, ʧʌapkanɨn pjoʧun kiappota naʧko, ʧʌapkanɨn koapka kjɛsanhal tˀe pʰiljohejo/

"When you report physics (physics results, low pressure is shown in default. You can get low pressure by reading a thermometer, low pressure is lower than standard pressure, and low pressure is needed in calculating high pressure."
물리학 보고서 작성시, 저압가는 기본으로 표시해요. 저압가는 수은주를 보면 알 수 있는데, 저압가는 표준 기압보다 낮고, 저압가는 고압가 예산할 때 필요해요.

Control /p#p/: /ʧipɛnɨn tʼukʼʌŋi isːnɨn ʧakɨn kɨlɨs nanhapi nɛke isːʌ jo. ʌmmanɨn keʌppʰumɨlo nanhap patauasːko, apʼanɨn jʌnmal saɨnpʰumɨlo nanhap patauasːko, ʌnninɨn saseŋtehoi saŋpʰumɨlo nanhap patauasːko, opʼanɨn pomulʧaʧʰki saŋpʰumɨlo nanhap patauasːʌ jo/

“There are four small containers with lids, or nanhap, at home. Mommy brought one Nanhap home for an open-business gift, daddy brought one Nanhap for an end-of-year gift, big sister brought one Nanhap for a prize for a sketch contest, and bigger brother brought one Nanhap home for a prize for a treasure hunt.”
집에는 뚜껑이 있는 작은 그릇 난합이 네개 있어요. 엄마는 개업품으로 난합 받아왔고, 아빠는 연말 사은품으로 난합 받아왔고, 언니는 사생대회 상품으로 난합 받아왔고, 오빠는 보물찾기 상품으로 난합 받아 왔어요.

Control /k#k/: /ʧʌnhak kataka ʧʌŋanɨn juʧʰiuʌn ʧʰinkutɨlkua hɛʌʧjʌsːko, ʧʌnhak kataka sʌŋanɨn ʧʰotɨŋhakkjo ʧʰinkutɨlkua hɛʌʧʌsːko, ʧʌnhak kataka kjʌŋanɨn ʧuŋhakjo ʧʰinkutɨlkua hɛʌʧjʌsːko, ʧʌnhak kataka nanɨn kotɨŋhakkjo ʧʰinkutɨlkua hɛʌʧjʌsːʌ jo/

“Jung-A said good-bye to friends from her kindergarten class when switching schools, Sung-A said good-bye to friends from her Elementary school when switching schools, Kyung-A said good-bye to friends from her Junior high school when switching schools, and I said good-bye to friends from my high school when switching schools.”
전학 가다가 정아는 유치원 친구들과 헤어졌고, 전학가다가 성아는 초등학교 친구들과 헤어졌고, 전학 가다가 경아는 중학교 친구들과 헤어졌고, 전학가다가 나는 고등학교 친구들과 헤어졌어요.

/p#k/ sequences: /nanhapɨn tʼukʼʌŋi isːnɨn ʧakɨn kɨlɨsiɛjo. ɨŋjoŋtojɛ suʌp sikanɛ nanhap kaʧiko jʌlʌkaci ʧakpʰumɨl mantɨlʧjo. nanhap kaʧiko tosilakɨl mantɨlko, nanhap kaciko panʧʰantʰoŋɨl mantɨlko, nanhap kaʧiko posʌkhamɨl mantɨlkito hejo/

“Nanhap is a container which comes with a lid. In applied pottery classes, we make various pieces using Nanhap. We make lunch boxes using Nanhap, containers for side dishes using Nanhap, and jewelry boxes using Nanhap.”
난합은 뚜껑이 있는 작은 그릇이에요. 응용도예 수업 시간에 난합 가지고 여러가지 작품을 만들죠. 난합 가지고 도시락을 만들고, 난합 가지고 반찬통을 만들고, 난함 가지고 보석함을 만들기도 해요.