

Russian assimilatory palatalization is incomplete neutralization

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Incomplete neutralization refers to phonetic traces of underlying contrasts in phonologically neutralizing contexts. The present study examines one such context: Russian assimilatory palatalization in C+j sequences. Russian contrasts plain and palatalized consonants, (e.g., /p/ vs. /pʲ/ with the “plain” consonants having a secondary articulation, involving retraction of the tongue dorsum (velarization/uvularization)). However, in the C+j sequences (e.g., /pjot/ ‘drink (3ps pres)’) the contrast between palatalized and plain consonants is neutralized, due to the palatalization of the plain consonants: /pjot/ → [pʲjot] (assimilatory palatalization). The purpose of the study is to explore whether the neutralization is complete. To do so, we conducted an electromagnetic articulography (EMA) experiment examining temporal coordination and the spatial position of the tongue body in underlyingly palatalized consonants and those derived from assimilatory palatalization. Articulatory results from four native speakers of Russian revealed that gestures in both conditions are coordinated as complex segments (i.e., they are palatalized consonants); however, there are differences across conditions consistent with the residual presence of a tongue dorsum retraction gesture in the “plain” obstruents. We conclude that neutralization of the plain-palatal contrast in Russian is incomplete—consonants in the assimilatory palatalization condition exhibit inter-gestural coordination characteristic of palatalized consonants along with residual evidence of an underlying tongue dorsum retraction (velarization/uvularization) gesture.



1. Introduction

Many instrumental investigations of phonologically neutralized contrasts have revealed that surface segments are not in fact identical to each other, as they contain phonetic traces of underlying contrasts. This phenomenon, often called incomplete neutralization, has been found for final devoicing in many languages. In the case of final devoicing, the voicing contrast is preserved in word-initial and word-medial positions. However, in the word-final position, both underlyingly voiced and underlyingly voiceless obstruents surface as voiceless. In German, for example, the voicing contrast of the alveolar stops in (1) is neutralized in word-final position, while being preserved in word-medial position.

- (1) Examples of final devoicing in German (Adopted from Roettger, Winter, Grawunder, Kirby, & Grice, 2014)

Rat /ʁa:t/ [ʁa:t] ‘council’

Räte /ʁæ:tə/ [ʁæ:tə] ‘councils’

Rad /ʁa:d/ [ʁa:t] ‘wheel’

Räder /ʁæ:de/ [ʁæ:de] ‘wheels’

However, previous studies have provided considerable evidence that such phonological neutralization is phonetically incomplete in German (e.g., O’Dell & Port, 1983; Port & Crawford, 1989; Roettger et al., 2014), as well many other languages, such as Catalan (e.g., Charles-Luce & Dinnsen, 1987), Dutch (e.g., Warner, Jongman, Sereno, & Kemps, 2004), Polish (e.g., Slowiaczek & Dinnsen, 1985), and Russian (e.g., Dmitrieva, Jongman, & Sereno, 2010; Kharlamov, 2012; 2014). Previous studies have shown that there are acoustic and articulatory differences between underlyingly voiced and voiceless obstruents, and such phonetic differences surface in the direction expected for the underlying form. More specifically, the underlyingly voiced obstruents tend to have shorter final stop closure durations, a shorter release burst, a longer preceding vowel, and/or more extensive voicing into closure than the underlyingly voiceless obstruents (Charles-Luce & Dinnsen, 1987; Dinnsen & Charles-Luce, 1984; Mascaró, 1987 for Catalan; Ernestus & Baayen, 2007; Warner et al., 2004 for Dutch; O’Dell & Port, 1983; Port & Crawford, 1989; Roettger et al., 2014 for German; Port & Crawford, 1989; Port & O’Dell, 1985; Slowiaczek & Dinnsen, 1985 for Polish; Dmitrieva et al., 2010; Kharlamov, 2012; 2014 for Russian).

Even though the majority of work on incomplete neutralization heavily focuses on final devoicing, the phenomenon is not restricted to this specific phenomenon. Other patterns that have long been described as neutralization have also turned out to be cases of incomplete neutralization: Flapping in American English (e.g., Herd, Jongman, & Sereno, 2010), coda aspiration in Eastern Andalusian Spanish (e.g., Gerfen, 2002), monomoraic lengthening in Japanese (e.g., Braver, 2019), vowel epenthesis in Levantine Arabic (e.g., Gouskova & Hall, 2009), vowel deletion in French (e.g., Fougeron & Steriade, 1997), blended vowels in Romanian (e.g., Marin, 2012), laryngeal neutralization in Korean (Lee, 2016), tone sandhi in Huai’an

Mandarin (e.g., Du & Durvasula, accepted), among others. There are also cases of what appears to be complete neutralization, such as Korean manner neutralization (Kim & Jongman, 1996; Lee, 2016).

Russian contrasts palatalized and plain consonants (so-called “soft” and “hard” consonants, respectively), as shown in (2) (e.g., Avanesov, 1972; Kochetov, 2002, 2006a, b; Padgett, 2001; 2003; Timberlake, 2004). Plain consonants, however, get palatalized when followed by a palatal glide, leading to neutralization of the contrast in this particular context (e.g., Avanesov, 1972; Timberlake, 2004).¹ For example, the contrast between /pʲ/ and /p/ (as in /pʲok/ vs. /pjot/) is neutralized due to the palatalization of the plain stop in the consonant-glide sequence.² Purely for expository convenience, we refer to the phonemic palatalized consonants as “underlying palatalization” and to the plain consonants preceding a palatal glide (and thus surfacing as palatalized) as “assimilatory palatalization.”

(2)	Plain	Underlying palatalization	Assimilatory palatalization
	/pot/ [pot] ‘sweat’	/pʲok/ [pʲok] ‘bake (3ps past)’	/pjot/ [pʲjot] ‘drink (3ps pres)’
	/buk/ [buk] ‘beech’	/bʲust/ [bʲust] ‘bust’	/bjut/ [bʲjut] ‘beat (3ps pl)’

Interestingly, however, previous studies have reported that “plain” consonants in Russian may be characterized by a secondary articulation involving retraction of the tongue dorsum (velarization or uvularization; see Litvin, 2014; Padgett, 2001; 2003; Roon & Whalen, 2019; Skaložub, 1963). That is, the words /pot/ and /buk/ in (2) may in fact be /p^vot^v/ and /b^vuk^v/. As Rubach (2000) argues, “there are no ‘plain’ consonants [in Russian, as] ... every consonant is articulated with one of the following two tongue-body positions: Forward movement and raising towards the hard palate (palatalization) or backward movement and raising towards the velum (velarization)” (p. 40). A similar view is taken by Padgett (2001). As phonological evidence for the underlying status of velarization, both authors cite the /i/-backing process, where this front vowel is consistently realized as central [i] after ‘plain’ consonants (e.g., /igr-a-tʲ/ [igratʲ] ‘to play (imperfective)’ vs. /s-igr-a-tʲ/ [sigratʲ] ‘to play (perfective)’). The backing of the vowel, the argument goes, is a natural assimilatory process triggered by an underlyingly velarized consonant: /C^v-i/ → [Ci] (which is a near-mirror image of the assimilatory palatalization process examined in this study, /C^v + j/ → [Cʲ]).

¹ Palatalization in C + j sequences is part of a larger assimilatory process of C + C^j sequences, the application of which depends on a range of factors, including the place and manner of the consonants, presence of morpheme boundaries, stress, etc. (Avanesov, 1972; Timberlake, 2004).

² There are only a small number of examples of consonant-glide sequences (C + j) and palatalized consonants (C^j) that form true minimal pairs: /ʲut/ ‘fierce’ vs. /ljut/ [ʲjut] ‘pour (3p. pl.);’ /kop’a/ ‘save (part.)’ vs. /kopja/ [kopʲja ~ kopja] ‘spear (gen. sg.);’ /sud’a/ ‘judge (part.)’ vs. /sudja/ [sudʲja] ‘judge (noun).’ Our materials contain only near minimal pairs because, for ease of measuring the primary constriction, we adhered to the additional requirement that the primary articulator is the lips.

Skalozub (1963) is one of the early studies that systematically examined plain and palatalized consonants in Russian, using X-ray imaging, static palatography, odontography, and partial oscillography. Based on articulatory results from four Russian speakers, Skalozub (1963) argued that at least some plain consonants – lateral /l/ and labial consonants – are strongly velarized. Recent ultrasound studies by Litvin (2014) and Roon and Whalen (2019) further confirmed that plain consonants in Russian have a secondary articulation. Litvin (2014) examined plain fricatives and /l/ across different vowel contexts [a] and [ɛ]. Ultrasound data from six Russian speakers revealed that, regardless of the vowel context, /l/ and /f/ were uvularized, while /s/ and /ʂ/ were either velarized or uvularized. Roon and Whalen (2019) have also shown that plain consonants in Russian are velarized (and/or uvularized), subject to intra-speaker variation. In particular, their articulatory data from three Russian native speakers revealed that there were consistent and discernable dorsal gestures regardless of the manner and syllable position (initial vs. final), at least within labials /p/, /f/, and /m/, but the location of constriction varied by speaker (velar to uvular). Overall, similar conclusions about a secondary posterior gesture of Russian labials were reached in MRI studies by Kedrova, Anisimov, Zaharov, and Pirogov (2008; four speakers) and Biteeva (2021; one speaker).

A question that arises from consideration of these patterns is whether the neutralization between plain and palatalized segments in Russian is phonetically (i.e., acoustically and/or articulatorily) complete. In other words, are there remaining traces of secondary velarization in words like [pʲjotʲ] and [bjutʲ], which are derived from /pʲjotʲ/ and /bʲjutʲ/, respectively? To this end, the current study examines the phonetic realization of underlying and assimilatory palatalization, in which the underlying contrast between plain and palatalized consonants has been claimed to be phonologically neutralized.

Patterns of incomplete neutralization have had a significant impact on the development of phonological theory. Most notably, incomplete neutralization has been argued to be incompatible with phonological models that order rules, such as assimilation, strictly before phonetic implementation, and consequently has motivated a variety of alternatives (e.g., Braver, 2019; Brockhaus, 1995; Dinnsen & Charles-Luce, 1984; Ernestus & Baayen, 2007; Piroth & Janker, 2004; Port & O'Dell, 1985; Roettger et al., 2014; Van Oostendorp, 2008). We return to this issue in the discussion, after establishing the Russian facts. In particular, we show how at least some cases of incomplete neutralization follow rather straight-forwardly from gesture overlap and blending, the standard machinery of Articulatory Phonology (e.g., Browman & Goldstein, 1986; 1989; 1992; 1995; Pouplier, 2020).

The remainder of this paper is structured as follows: The rest of Section 1 provides background on Articulatory Phonology as well as past acoustic and kinematic studies on Russian palatalization. We then lay out our hypotheses and predictions in Section 2. In particular, we hypothesize that the gestural blending of two secondary articulation gestures (palatalization and

velarization) would lead to incomplete neutralization of the plain-palatalized contrast in Russian. Then, we transition to an empirical test of the hypotheses. We conducted an Electromagnetic Articulography (EMA) experiment examining temporal coordination and the spatial position of the tongue body for underlying and assimilatory palatalization. The methods of the experiment are described in Section 3, and the results are reported in Section 4. The discussion is presented in Section 5.

1.1. Articulatory Phonology

Articulatory Phonology (henceforth, AP) provides a natural framework for describing incomplete neutralization. In this theory, the primitive phonological units are gestures. Gestures are discrete and abstract in the sense that they are specifically defined by a set of dynamical parameters that characterize each gesture distinctively (e.g., Browman & Goldstein, 1986; 1989; 1992; 1995; Pouplier, 2020). In AP, gestures are specified with respect to vocal tract variables. AP utilizes a set of gestural descriptors that distinguish contrastive gestures: Constriction degree (CD) and constriction location (CL). Tract variable goals (input values for CD and CL) determine the inherent spatial aspect. For example, /s/ and /ʃ/ differ in their values for CL (*alveolar* vs. *postalveolar*, respectively), while /s/ and /t/ differ in their values for CD (*critical* vs. *closed*, corresponding to fricative-like and stop-like constrictions). Finally, a dynamical control variable, stiffness (k), specifies the intrinsic temporal aspect of each gesture.

The activation of gestures over time can be displayed in a gestural score (e.g., Browman & Goldstein, 1989; 1992). For example, a gestural score for the word ‘pen’ /pɛn/ would include the CD and CL of each gesture as well as the intergestural timing. Specifically, there are two gestures associated with the initial /p/: a Lip closure gesture and a wide glottal gesture. The tongue body gesture for /ɛ/ also starts at the beginning of the utterance overlapping with the gestures associated with /p/. The final consonant /n/ also has two gestures: A tongue tip closure and a velic opening, which also overlap with the preceding vowel gesture. The overlap between the velic opening and the vowel gesture leads to partial nasalization of the vowel.

Browman and Goldstein (1989) proposed that phonological phenomena (such as deletion, insertion, assimilation, and weakening) can be captured by two general processes: ‘Hiding’ and ‘blending’ of gestures. When gestures significantly overlap on the different articulatory tiers, one gesture may hide the other acoustically, despite both gestures still being present articulatorily. For example, the apparent deletion of /t/ in ‘perfect memory’ ([ˈpʰɚfɛkt ˈmɛməɹi]) at a fast speech rate is better described as gestural hiding (Tiede, Perkell, Zandipour, & Matthies, 2001): The alveolar gesture for /t/ completely overlaps with the preceding velar gesture for /k/ and the following labial gesture for /m/, resulting in the former consonant being acoustically hidden. On the other hand, when two gestures overlap on the same articulatory tier, they compete with each other to achieve their own articulatory targets. This kind of overlap may lead to ‘blending’ of the

dynamical parameters of these gestures. The gestural outcome of blending is different from that of either of the individual gestures. Instead, the outcome falls somewhere in between the two gestures, the extent of which depends on the blending strength of each gesture. For example, as discussed earlier, the backing of /i/ to [i] after plain consonants in Russian is better described as a gestural blending between /i/ and the velarization gesture of the preceding consonant. In particular, the gesture for /i/ and /ʲ/ overlap on the same TB tract variable, resulting in the blending of CD and CL parameters for both /i/ (narrow, palatal) and /ʲ/ (critical, velar). In this blending process, the gesture with the stronger blending parameter (e.g., the gesture for /i/) has a greater influence on the kinematics, which may still be impacted by the gesture with weaker blending strength (e.g., the velarization gesture).

In AP, incomplete neutralization does not require any special machinery. It follows from independently motivated aspects of the theory (i.e., the blending of two gestures such that one gesture dominates control of the articulator but the other still has some influence).

1.2. Past results on Russian palatalization

Independent of whether the “plain” consonant in the consonant-glide sequences is palatalized or not, the consonant-glide sequence itself is not necessarily phonetically identical to the palatalized consonant. In fact, previous studies reported that there is a perceivable difference between palatalized consonants (C^j) and consonant-glide sequences (C + j). For example, Ladefoged and Maddieson (1996, p. 364) showed spectrograms comparing the Russian initial palatalized labial stop /p^j/ and a labial stop + palatal glide sequence /pj/ (/p^jotr/ ‘Pyotr (name)’ vs. /pjot/ ‘drink (3ps pres)’). They observed that for the former F2 began falling immediately after the consonant release, while for the latter the F2 decrease began later, after a steady-state period.

In a more extensive study of the contrast, Diehm (1998) examined acoustic characteristics of various palatalized consonants (C^j) and corresponding consonant-glide sequences (C + j) produced by native speakers and learners of Russian. Results from eight native speakers (four male and four female) revealed that consonant-glide sequences (C + j) exhibited significantly higher F2 at the transition onset than palatalized consonants (C^j) (2704 Hz vs. 2362 Hz for females; 2233 Hz vs. 2012 Hz for males). In addition, she reported that consonant-glide sequences (C + j) showed a significantly longer F2 steady-state duration than palatalized consonants (C^j) (on average 117 ms vs. 33 ms for females; 102 ms vs. 25 ms for males).

In addition, Suh and Hwang (2016) examined palatalized consonants (C^j) and consonant-glide sequences (C + j) in Russian, comparing them to a palatal glide in Korean. To measure glide duration, they first examined the vocalic duration comprising the j + V portion (from the onset of the vocoid to the offset of the vowel). They further calculated the duration ratio of the j + V portion to the pure vowel duration in CV. The results from five Russian native speakers revealed

that the vocalic duration comprising the j + V portion of CjV syllables was significantly longer than the j + V portion of C'V syllables.³

Articulatory studies of Russian have shown differences that are consistent with the observations from acoustic data. Kochetov (2006b) examined the effect of syllable position on gestural organization using kinematic data from EMMA (Electromagnetic Midsagittal Articulometer). In particular, he compared articulatory patterns exhibited by the palatalized stop /pʲ/, the plain stop /p/, and the palatal glide /j/ produced by four native speakers of Russian. The results revealed that the palatal gesture was longer when it occurred as a segment in /p#j/ sequences than when it occurred as secondary palatalization in /pʲ/. In addition, and of particular interest to the present study, Kochetov (2006b) showed that the relative timing of the labial gesture and the palatal glide gesture in stop-glide sequences (/p#j/) differed from the relative timing of these gestures in palatalized stops like /pʲ/. More specifically, the glide gesture was achieved later in the stop-glide sequence /p#j/ than in the glide gesture for the palatalized stop /pʲ/. However, since the stop-glide sequence used in the study involved a word boundary, it is unclear whether the delayed glide gesture in the segment sequence was due to the characteristics of the segment sequence or from the effect that the prosodic boundary may have had on articulatory timing. Consequently, the difference in the delayed achievement lag for /p#j/ and /pʲ/ is not a valid criterion for accessing incomplete neutralization of palatalized and plain consonants in assimilatory palatalization, nor is it a valid criterion for distinguishing complex segments and segment sequences more generally.

The acoustic and articulatory results summarized above confirm that there are phonetic cues to the difference between palatalized consonants (Cʲ) and consonant-glide sequences (C + j). These differences likely reflect the structural difference between a glide gesture as a secondary articulation and a glide gesture as a separate segment. Crucially, however, the acoustic differences between consonant-glide sequences (C + j) and palatalized consonants (Cʲ) do not provide any information as to whether the “plain” consonant in the consonant-glide sequences is palatalized or not. To evaluate incomplete neutralization, it is first necessary to establish whether the consonant preceding a palatal glide is indeed palatalized.

Such a quantification of palatalization in Russian might be achieved by examining temporal coordination for complex segments and segment sequences, as proposed by Shaw, Oh, Durvasula, and Kochetov (2021). The authors hypothesized that complex segments have a temporal basis—two articulatory gestures, G1 and G2, belong to the same complex segment if the onset of G2 is temporally coordinated with the onset of G1. In contrast, two gestures belong to sequences of segments if the onset of G2 is temporally coordinated with the offset of G1. These competing coordination relations were explored by investigating how the lag between the onset of G1 and the onset of G2

³ The Korean results are not discussed as they are not relevant to the current paper.

varied with G1 duration. The key finding involved differences between English consonant-glide sequences [p + j], [b + j], [m + j], and [v + j] (e.g., *pew*, *butte*, *muse*, *view*), and Russian palatalized labials [pʲ], [bʲ], [mʲ], [fʲ], [vʲ]. Articulatory results from four English native speakers and four Russian native speakers revealed that for English stop-glide sequences, as consonant duration increased, so too did the lag between consonant and glide gestures (see **Figure 1**). In contrast, for Russian palatalized consonants, variation in the consonant duration had no effect on the onset lag. That is, English stop-glide sequences showed the hypothesized temporal basis for segment sequences, while the palatalized consonants in Russian exhibited the hypothesized temporal basis for complex segments. The pattern of covariation successfully differentiated between palatalized labials in Russian, cases of underlying palatalization, and labial-glide sequences in English. In this paper, we examine whether this pattern of covariation differentiates two types of Russian sequences: Underlying palatalization vs. assimilatory palatalization.

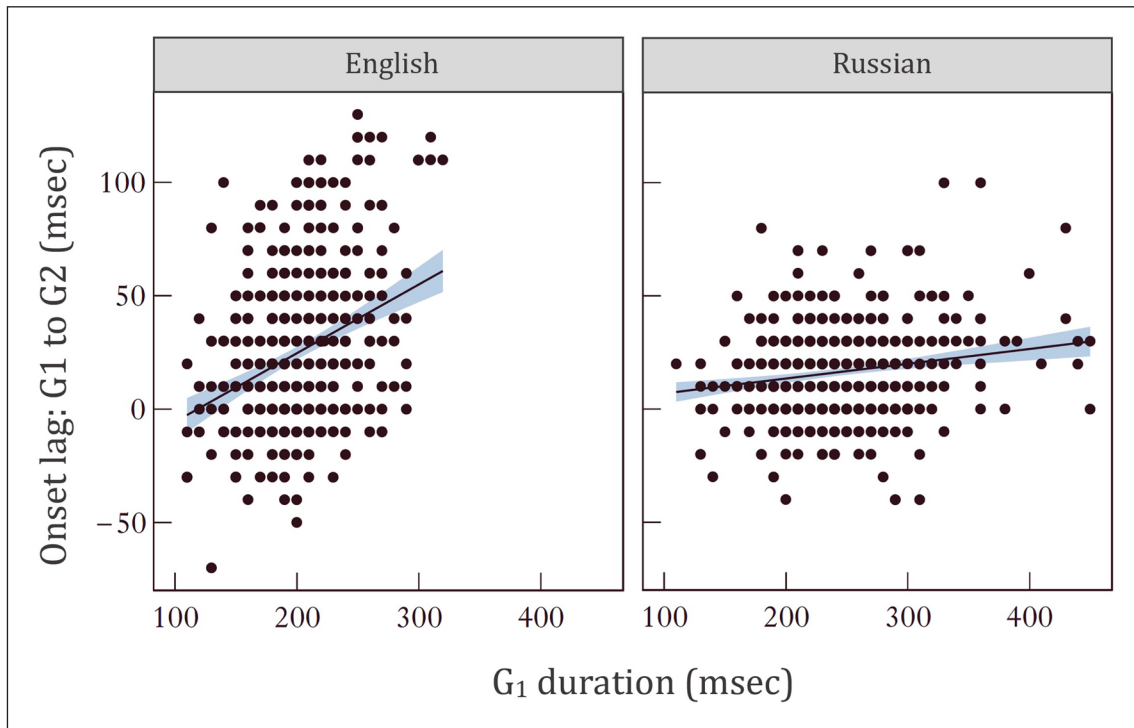


Figure 1: A scatter plot of the effect of G1 duration (x-axis) on onset-to-onset lag (y-axis) for each language. English (a), which parses the gestures into segment sequences, shows a strong positive correlation while Russian (b), which parses the gesture into complex segments, shows no correlation (adapted from Shaw et al., 2021, p. 464).

In the next section, we present our hypotheses regarding incomplete neutralization of underlying and assimilatory palatalization in Russian, making use of the temporal diagnostics for complex segmenthood.

2. Research questions and predictions

The fundamental question of this study is whether the “plain” consonant in the consonant-glide sequences (assimilatory palatalization) is palatalized, and, if so, whether this assimilatory palatalization is phonetically distinct from underlying palatalization. We have divided this into two sub-questions as follows:

- Research question 1: Do underlying palatalization (e.g., /b^j/) and assimilatory palatalization (e.g., /b + j/ [b^j]) both exhibit the temporal coordination characteristic of complex segments?
- Research question 2: Do underlying palatalization (e.g., /b^j/) and assimilatory palatalization (e.g., /b + j/ [b^j]) exhibit any systematic spatial and/or temporal differences?

The first research question addresses whether the two cases of Russian palatalization show the inter-gestural coordination of palatalized consonants (i.e., complex segments) or of consonant-glide sequences (segment sequences). Using the temporal diagnostics of complex segments and segment sequences (Shaw et al., 2021), we examined neutralization of underlying and assimilatory palatalization in Russian. If plain consonants preceding a palatal glide (assimilatory palatalization) are palatalized, assimilatory palatalization will exhibit the temporal coordination of complex segments, just like palatalized consonants (underlying palatalization). That is, if Russian palatalization exhibits neutralization, both underlying and assimilatory palatalization will show the temporal coordination of complex segments. In contrast, if Russian palatalization exhibits no neutralization, the underlying palatalization will show the temporal coordination of complex segments, while the assimilatory palatalization will exhibit the temporal coordination of segment sequences.

The second research question addresses whether the neutralization is complete (if the neutralization exists). That is, if there are spatial and/or temporal differences between the underlying and assimilatory palatalization, and if such phonetic differences surface in the direction expected for the underlying form, it would be considered incomplete neutralization. Assuming that plain consonants also have secondary velarization, we examine the completeness of the neutralization using the spatial position of the tongue body, as well as the temporal lag between the onset of the labial gesture and the onset of the palatal gesture.

Consequently, there are three possible outcomes, depending on the temporal organization and spatial and/or temporal differences of underlying and assimilatory palatalization: 1) No neutralization, 2) complete neutralization, and 3) incomplete neutralization.

- No neutralization: Underlying palatalization shows temporal coordination of complex segments. In contrast, assimilatory palatalization exhibits temporal coordination of

segment sequences, showing that the plain consonants are not palatalized in this context and that the contrast between palatalized and plain consonants is preserved. Consequently, there are consistent spatial and/or temporal differences of underlying and assimilatory palatalization.

- Complete neutralization: Both underlying and assimilatory palatalization cases exhibit the temporal coordination of complex segments, showing that the contrast between palatalized and plain consonants is neutralized in this context. Furthermore, there are no spatial and/or temporal differences between underlying and assimilatory palatalization, showing that the neutralization is complete.
- Incomplete neutralization: Both underlying and assimilatory palatalization cases show the temporal coordination of complex segments, and yet there are phonetic traces — spatial and/or temporal differences — indicative of the underlying categories (i.e., a palatal gesture for the palatal glide and a velar/uvular gesture for the plain consonants).

Given that plain consonants have secondary velarization (Litvin, 2014; Roon & Whalen, 2019; Skalozub, 1963), we predict that there will be a significant overlap between two secondary articulation gestures (palatalization and velarization/uvularization) in assimilatory palatalization. This will result in the gestural blending of palatalization and velarization/uvularization, and, in turn, will lead to incomplete neutralization of underlying and assimilatory palatalization in Russian.

	(a) Underlying palatalization /bʲ/	(b) Assimilatory palatalization /bʲ+j/
Lips	[clo, labial]	[clo, labial]
TB	[narrow, palatal]	[crit, velar] [narrow, palatal]

Figure 2: Predicted gestural scores for underlying (a) and assimilatory palatalization (b) in Russian (incomplete neutralization).

Figure 2 illustrates the hypothesis that motivates our predictions. It shows hypothesized gestural scores for underlying and assimilatory palatalization in Russian (see Section 1.1 for background on gestural scores). For underlying palatalization (panel a), there is a labial gesture and a palatal gesture, which start at the same time; for assimilatory palatalization (panel b) there is additionally a velar gesture overlapping in time with the labial and palatal gestures. Gestural overlap on the same tract variable, in this case, palatalization and velarization on the

TB tract variable, would lead to gestural blending between these two gestures. Depending on the language-specific gestural blending parameters (see for discussion, e.g., Iskarous, McDonough, & Whalen, 2012), blending could result in a slightly more retracted tongue position for assimilatory palatalization compared to underlying palatalization, which only has the palatal gesture on the TB tract variable. Consequently, this difference would lead to incomplete neutralization between underlying and assimilatory palatalization in Russian.

3. Methods

3.1. Participants

Four native speakers of Russian participated in this experiment (three female and one male). All speakers were in their 20s at the time of recording and living in the United States. The Russian speakers were born in Russia and moved to the United States as adults.

3.2. Materials

The materials included six closely matched pairs representing two conditions: Palatalized consonants vs. plain consonants preceding a palatal glide (**UNDERLYING** vs. **ASSIMILATORY PALATALIZATION**). In order to be able to parse the consonantal gesture and the palatal gesture clearly, we imposed a further restriction that the consonant be a labial consonant. Consequently, it was impossible for us to find perfect minimal pairs, and we had to use near minimal pairs. In all cases, the primary word stress falls on the first syllable, and the vowel immediately following is either /u/ or /o/, as shown in **Table 1**. The target words were read in the carrier phrase: *Она __ повторила /o'n-a __ po-vto'r-i-l-a / [ʌ'nə __ pəftʌ'rʲilʌ]. 'She __ repeated.'*

Palatalized consonants (UNDERLYING palatalization)			Consonant-glide sequences (ASSIMILATORY palatalization)				
word	IPA	Gloss	word	IPA		gloss	
<i>пёк</i>	/pʲokʲ/	[pʲokʲ]	bake (3ps past)	<i>пьёт</i>	/pʲj-o-tʲ/ ⁴	[pʲjotʲ]	drink (3ps pres)
<i>бюст</i>	/bʲusʲtʲ/	[bʲusʲtʲ]	bust (breast)	<i>бьют</i>	/bʲj-u-tʲ/	[bʲjutʲ]	beat (3pp pres)
<i>мю</i>	/mʲu/	[mʲu]	Му (μ)	<i>мью</i>	/mʲju/	[mʲju]	a Pokémon name

(Contd.)

⁴ In the verbs with the /Cj-/ sequence in **Table 1**, the glide is derived from the vowel /i/ (e.g., /pj-o-tʲ/ 'drink (3ps pres)' from /pi-tʲ/ 'drink (inf)').

Palatalized consonants (UNDERLYING palatalization)			Consonant-glide sequences (ASSIMILATORY palatalization)			
word	IPA	Gloss	word	IPA	gloss	
Фёдор	/fʲodʲorʲ/	[fʲodʲrʲ]	фьорд	/fʲjorʲdʲ/	[fʲjorʲdʲ]	fjord
вез	/vʲozʲ/	[vʲozʲ]	вьешь	/vʲj-o-ʃʲ/	[vʲjofʲ]	weave (2ps pres)
вёдра	/vʲodʲrʲ-a/	[vʲodʲrʲʌ]	вьём	/vʲj-o-tʲ-sʲa/	[vʲjotsʲʌ]	weave (3ps pres refl)

Table 1: Russian target words.

3.3. Procedure

Data collection took place in the Phonetics Lab at Yale University’s Department of Linguistics. The articulatory and acoustic data were simultaneously recorded by means of *5D Electromagnetic Articulography (EMA)* and an audio-recording setup. To collect articulatory data, nine sensors were attached to the participants: Three sensors for tongue movements, two for lip movements (upper and lower lips), one for jaw movements (lower incisor), and three for reference (the nasion and left/right mastoids). Three sensors on the tongue, tongue tip (TT), tongue blade (TB), and tongue dorsum (TD), were attached along the sagittal midline of the tongue, being placed behind the tongue tip approximately one cm, three cm, five cm, respectively. Sensors were tracked using the *NDI Wave Speech Production System*. Reference sensors were used to computationally correct for head movements. Each participant produced between 15 and 30 repetitions of the target sentences, yielding a total of 1166 tokens. As a post-processing procedure, the data was computationally corrected for head movements and rotated to the occlusal plane so that the bite of the teeth serves as the origin of the spatial coordinates. We also calculated a lip aperture trajectory, as the Euclidean distance between the upper and lower lip sensors. All trajectories were smoothed using the robust method described in Garcia (2010).

3.4. Analysis

The post-processed data was visualized in *MVIEW* (Tiede, 2005). Changes in Lip Aperture (LA), computed as the Euclidean distance between the upper and lower lip sensors over time, were used to identify labial gestures. The TB sensor indexed the palatal gesture. Gestural landmarks were parsed with reference to the velocity signal using the *findgest* function in *MVIEW*. Specifically, the gesture *Onset* and *Target* landmarks were labeled at 20% of peak velocity in the movement toward constriction (see **Figure 3**). *Release* and *Offset* landmarks were labeled at a 20% threshold

of peak velocity in the movement away from constriction. As illustrated in **Figure 4**, the two key temporal intervals computed from these articulatory landmarks were (1) G_1 duration, defined as the interval from *Onset* to *Offset* of the labial gesture; and *onset-to-onset lag*, defined as the interval between the *Onset* of the labial gesture (G_1) and the *Onset* of the palatal gesture (G_2). In addition to temporal coordination, the current study measured the longitudinal position (front-back) of the TB sensors at palatal gesture onset to assess any impact of underlying velarization on the realization of assimilatory palatalization. The spatial position of the TB sensors was normalized using z-scores for each speaker. Before proceeding with statistical analysis, we removed outliers that were greater than three standard deviations from the speaker-specific mean value of either G_1 duration, seven tokens removed (0.6% of the data), or *onset-to-onset lag*, 18 tokens removed (1.6% of the data).

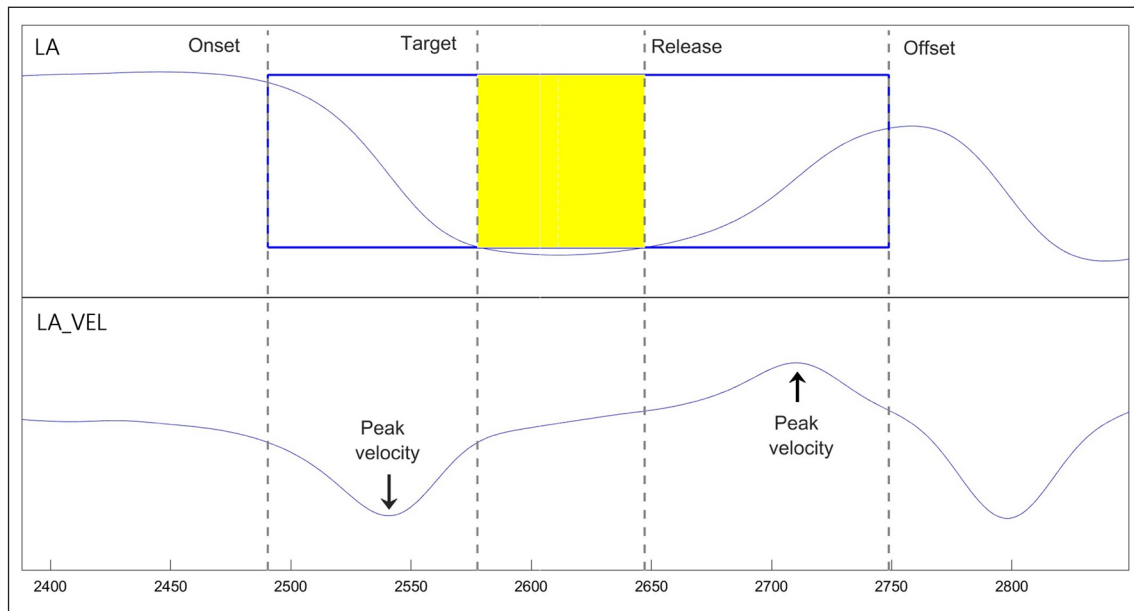


Figure 3: Example of gesture parse for a labial gesture. The gestural landmarks, Onset, Target, Release, Offset, are labeled at 20% thresholds of peak velocity.

To examine the neutralization status of Russian palatalization, the correlation between *onset-to-onset lag* and G_1 duration was analyzed. As G_1 duration varies, we ask whether *onset-to-onset lag* will positively covary, or whether these intervals will be statistically independent. If the contrast between a palatalized consonant (underlying palatalization) and a plain consonant preceding a palatal glide (assimilatory palatalization) in Russian is preserved (no neutralization), underlying palatalization will show no correlation between consonant duration and *onset-to-onset lag*, while for assimilatory palatalization, *onset-to-onset lag* will increase with G_1 duration, leading to a positive correlation between them. However, if the contrast is neutralized, both the underlying and assimilatory palatalization will exhibit no correlation between G_1 duration and *onset-to-onset lag*.

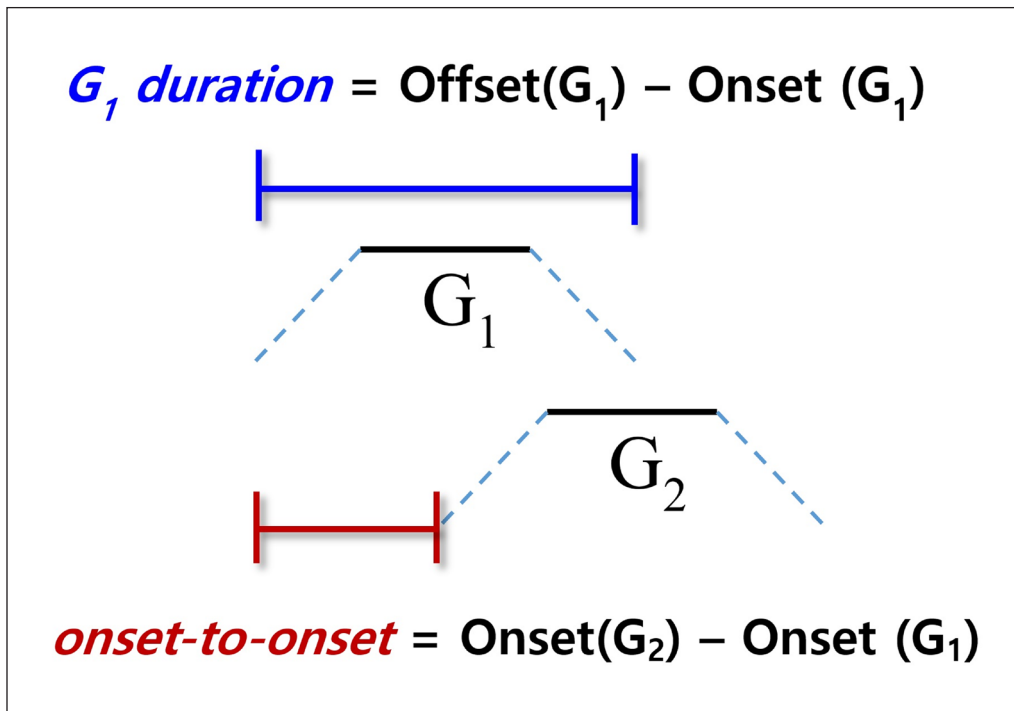


Figure 4: Schematic depiction of the two intervals, G_1 duration and onset-to-onset lag. G_1 refers to the labial gesture and G_2 refers to the palatal gesture.

We, therefore, treat *onset-to-onset lag* as a dependent variable and evaluate whether G_1 duration and *Condition* are significant predictors. We fit linear mixed-effects models to onset-to-onset lag using the *lme4* package in R (Bates, Mächler, Bolker, & Walker, 2014). To a baseline model, consisting of by-subject and by-item random slopes for G_1 duration and random intercepts for subjects and items, we added fixed factors of interest incrementally. First, we added G_1 duration, then *Condition* (UNDERLYING vs. ASSIMILATORY, with UNDERLYING as the reference level), and finally the interaction between G_1 duration and *Condition*. This gives a set of four nested linear mixed-effects models. We evaluated the significance of each fixed factor through *anova*. The fixed factor of primary interest is the interaction term: G_1 duration X *Condition*. If the contrast is not neutralized, G_1 duration is predicted to have a positive influence on *onset-to-onset lag* for assimilatory palatalization but not for underlying palatalization. On the other hand, if the contrast is neutralized, both palatalizations will exhibit the same pattern (i.e., the G_1 duration X *Condition* interaction will not be significant and there will be no correlation between G_1 duration and *onset-to-onset lag*).

To assess the incompleteness of the neutralization, we also examined the effect of *Condition* on the *TB position* at palatal gesture onset. If the neutralization is complete, there will be no difference in the *TB position* across conditions. However, if the neutralization is incomplete, the

assimilatory palatalization will exhibit a more retracted tongue position than the underlying palatalization. To test this, separate linear mixed-effects models were run with *TB position* as a dependent variable and *Condition* as a fixed factor. All models included *by-Speaker* and *by-Item* random slopes of TB position.

4. Results

4.1. Kinematic trajectories and distribution

We first examine the continuous kinematic trajectories of relevant articulators for UNDERLYING and ASSIMILATORY palatalization in Russian. **Figure 5 (a)** illustrates kinematic trajectories for the item /b^hust/ (UNDERLYING palatalization), as produced by the four Russian speakers in the study. The figure plots the LA trajectory in the upper panels and the TB trajectory in the lower panels. Each trajectory is represented by a different color; the thick dotted line shows the average trajectory. The temporal window of the trajectories is 600 ms long, spanning from 100 ms before the onset landmark of the lip aperture gesture to 500 ms following this landmark. The level of variability in the magnitude of the gestures varies by subject. For R2, most tokens occur tightly clustered around the mean; R1 and R3 show more variability, and R4 shows even more. On the other hand, the relative timing of the gestures appears similar across speakers — the fall in the LA trajectory, indicating the closing of the lips tends to coincide with the rise of the TB for the palatal gesture. To facilitate comparison, vertical gray lines indicate when the LA trajectory starts to fall (based on the average trajectory) and when TB starts to rise (also based on the average).

Figure 5 (b) shows kinematic trajectories for the item /b^hjut^h/ (ASSIMILATORY palatalization). The level of variability in the magnitude of the gestures appears similar to the UNDERLYING palatalization case. Regarding the relative timing of the gestures for the token /b^hjut^h/, the rise for the TB movement tends to follow shortly after the fall of the LA trajectory.

Next, we present the distribution of the continuous variables, the key intervals for the temporal coordination analysis: G_1 duration (labial gesture; See **Figure 6**) and onset-to-onset lag (**Figure 8**). For both intervals, we present the distribution by *Condition*: UNDERLYING vs. ASSIMILATORY palatalization. Also, for completeness, we plot the distribution of G_2 duration (palatal gesture; see **Figure 7**). This measurement is not directly related to our research questions, but is included for reference.

As shown in **Figure 6**, the G_1 duration measures have a slightly right-skewed distribution with a long right tail, which is common for temporal measurements of speech associated with linguistic units. This is true for the distributions of palatal gesture duration as well as onset-to-onset lag. Notably, however, the distributions of G_1 duration for UNDERLYING and ASSIMILATORY palatalization overlap heavily, with similar means and variance. On the other hand, as shown in **Figure 7**, ASSIMILATORY palatalization tends to have a longer palatal gesture than UNDERLYING

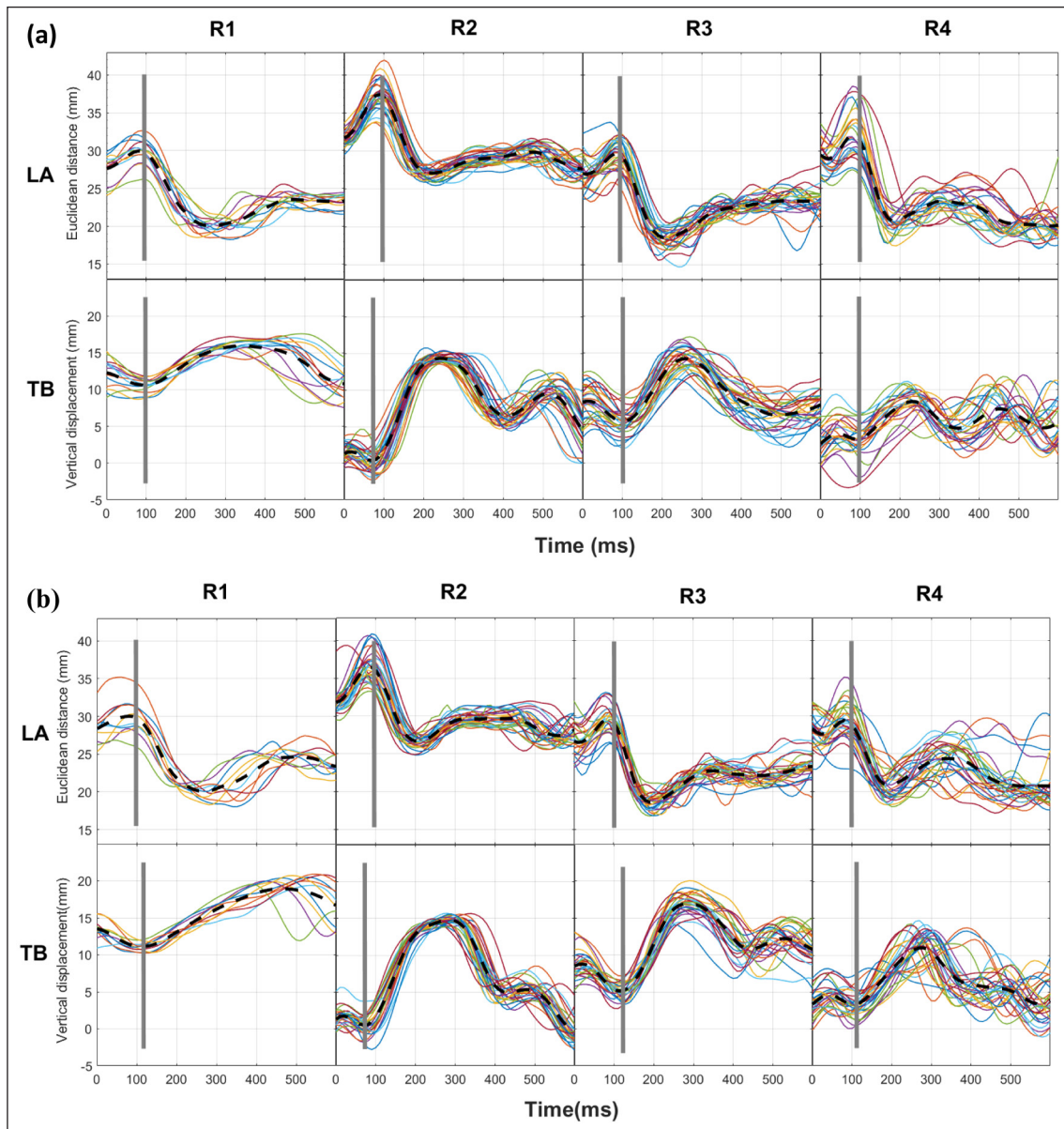


Figure 5: (a) Tokens of /bʲusʲtʲʲ/ (UNDERLYING palatalization); (b) Tokens of /bʲjutʲʲ/ (ASSIMILATORY palatalization). The thick dashed black line represents the average trajectory for each speaker. The top panels show the lip aperture (LA) trajectory. The bottom panels show the tongue blade (TB) in the vertical dimension. The time window of 600 ms extends from 100 ms before the onset of lip aperture movement to 500 ms after the onset of lip aperture movement. The vertical gray lines indicate the onset of LA lowering and the onset of TB raising, both based on the average trajectory.

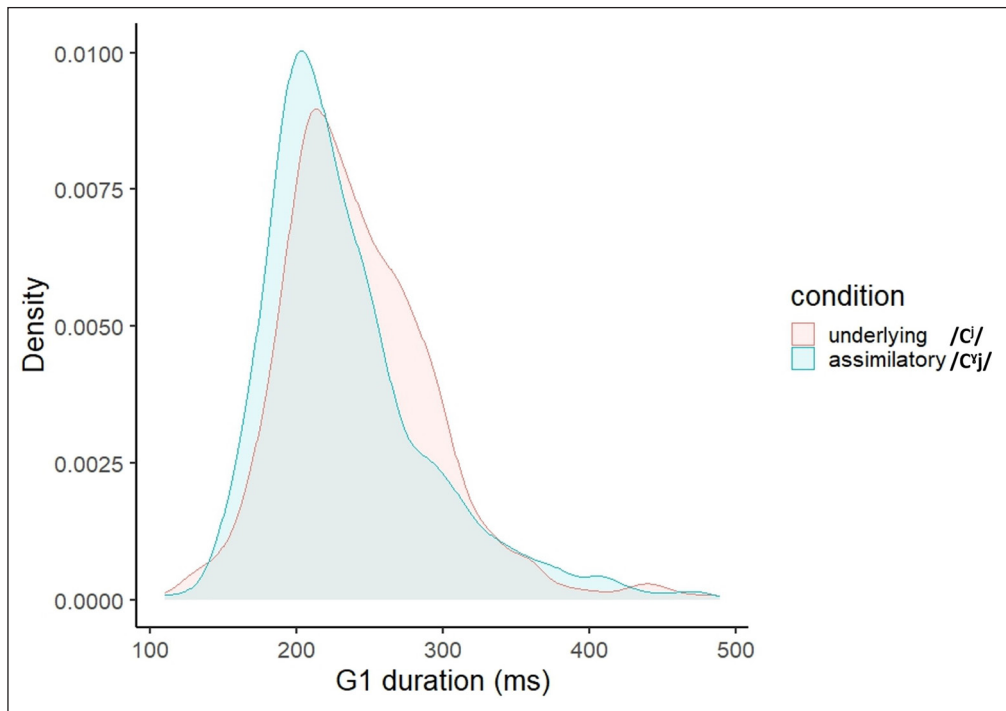


Figure 6: The distribution of G1 (labial consonant) duration by Condition.

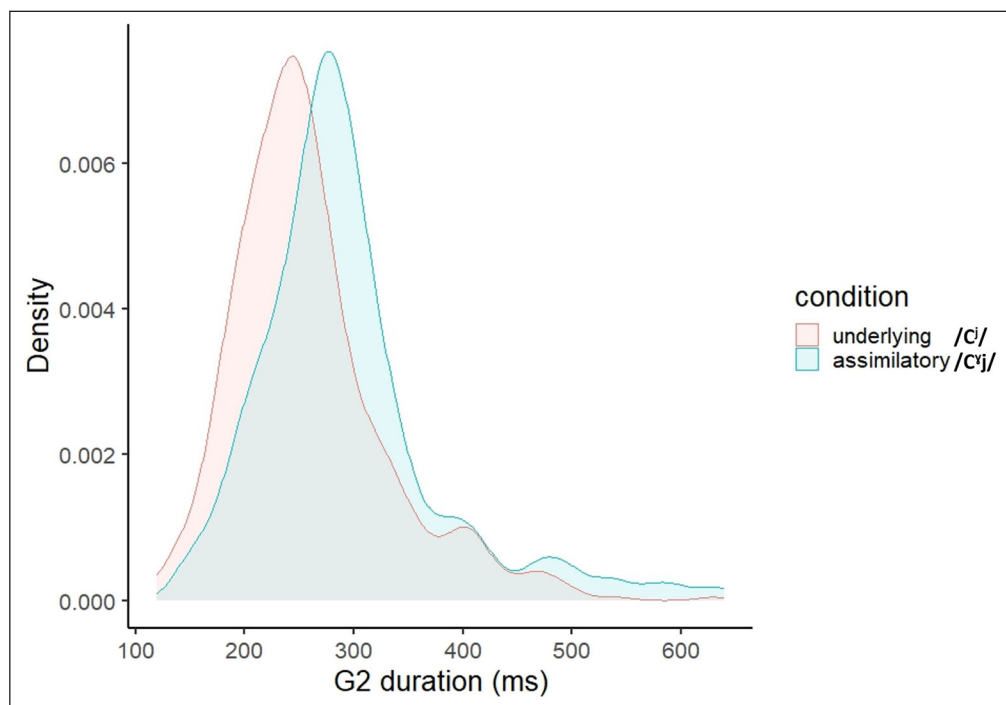


Figure 7: The distribution of G2 (palatal gesture) duration by Condition.

palatalization, consistent with the previous findings (Kochetov, 2006b). The distribution of onset-to-onset lag shows that ASSIMILATORY palatalization tends to have a longer onset-to-onset lag than UNDERLYING palatalization and the distributions differ in shape, with UNDERLYING palatalization having a sharp peak with more values close to the mean (see **Figure 8**).

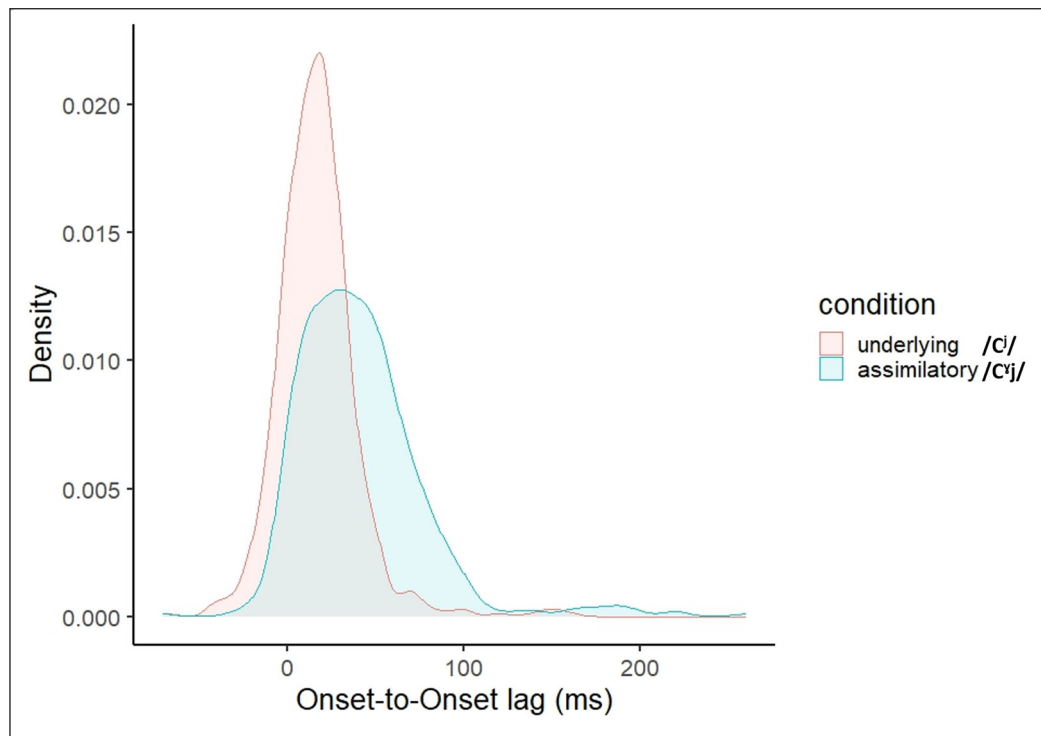


Figure 8: The distribution of onset-to-onset lag measurements by *Condition*.

4.2. Temporal coordination

As discussed in Section 2, both the UNDERLYING and ASSIMILATORY palatalization (e.g., /bʲ/ and /bʲ + j/, respectively) are expected to show no correlation between *G1 duration* and *onset-to-onset lag*, if both are palatalized. If one (most likely the ASSIMILATORY palatalization) turns out to behave like a segment sequence, then the *onset-to-onset lag* will increase with *G1 duration*, leading to a positive correlation between them, as has been observed for English stop-glide sequences (**Figure 1**).

Figure 9 plots the relation between *G1 duration* (x-axis) and *onset-to-onset lag* (y-axis) across *Condition* for each speaker. To illustrate the trend in the data, a least squares linear regression line is fit to each panel. The R^2 value of each regression line from **Figure 9** is summarized in **Table 2**. The regression line is nearly flat — precisely the pattern predicted for complex segments (Shaw et al., 2021). Notably, this pattern was observed for both UNDERLYING and ASSIMILATORY

palatalization, indicating that plain consonants preceding glides (ASSIMILATORY palatalization) are also palatalized. This is consistent with the view that the contrast between palatalized and plain consonants is neutralized with respect to temporal coordination.

To assess the statistical significance of the trends in **Figure 9**, we fit a series of linear mixed-effects models to the data (for additional detail, see Section 3.4). As shown in **Table 3**, the addition of *Condition* as a fixed factor improves the baseline model, which contains only random effects of subject and item ($\chi^2 = 23.17, p < 0.001$). This suggests that the onset-to-onset lag significantly differs by *Condition*, as can be observed in **Figure 8** and **Figure 9**. Crucially, however, the addition of G_1 duration does not improve the model ($\chi^2 = 2.02, p = 0.16$), and neither does the addition of the interaction term ($\chi^2 = 0.86, p = 0.35$). The lack of improvement indicates that there is no evidence of a correlation between G_1 duration and onset-to-onset lag, which is predicted by complex segment timing. In the best-fitting model for temporal coordination (onset-to-onset \sim *Condition* + (1 + G_1 duration | subject) + (1 + G_1 duration | item)), the main effect of *Condition* is significant ($t = 8.2, p < 0.001$). Specifically, ASSIMILATORY palatalization is estimated to be 25.4 ms longer than UNDERLYING palatalization in onset-to-onset lag. This pattern is highlighted in **Figure 10**, which provides a box plot of onset-to-onset lag across *Condition*. **Figure 11** shows that this pattern is consistent across speakers.

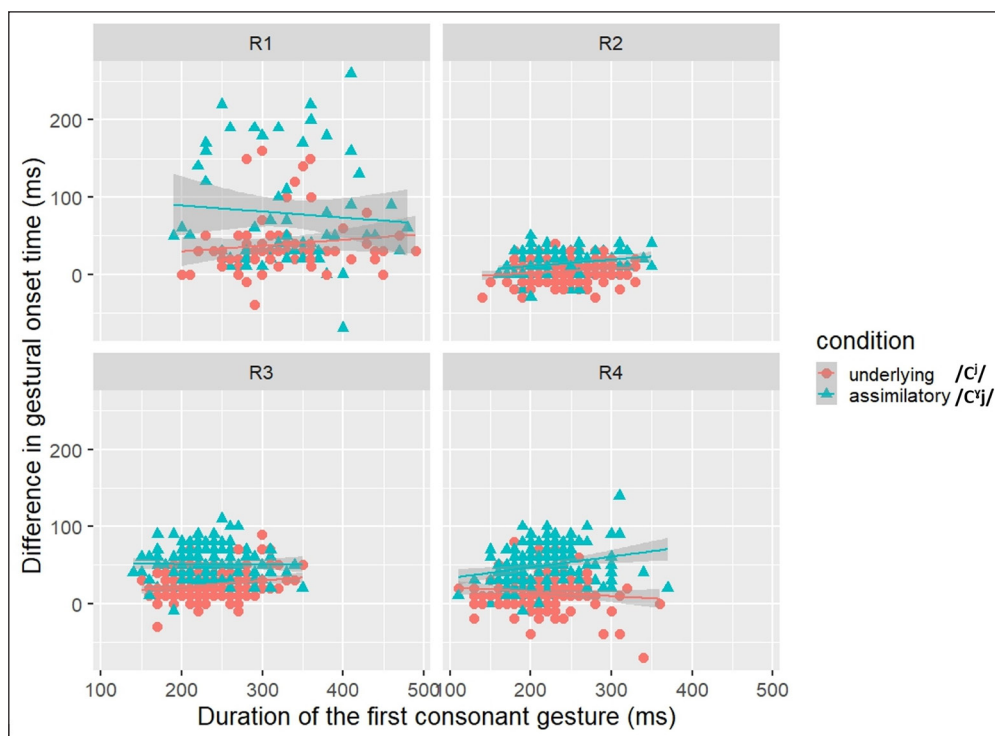


Figure 9: A scatter plot of the effect of G_1 duration (x-axis) on onset-to-onset lag (y-axis) across *Condition* for each speaker.

<i>Condition</i>	<i>R1</i>	<i>R2</i>	<i>R3</i>	<i>R4</i>
UNDERLYING	0.018	0.026	0.044	0.013
ASSIMILATORY	0.0061	0.061	0.00001	0.052

Table 2: Summary of R^2 value of each regression line from **Figure 9**.

LME Model comparison (<i>onset-to-onset~</i>)	Df	AIC	logLik	χ^2	Pr(> χ^2)
1 + (1 + G1 duration subject) + (1 + G1 duration item)	8	10511	-5247.3	NA	NA
1 + Condition + (1 + G1 duration subject) + (1 + G1 duration item)	9	10490	-5235.7	23.17	<0.001
1 + Condition + G ₁ duration + (1 + G1 duration subject) + (1 + G1 duration item)	10	10490	-5234.7	2.02	0.16
1 + Condition * G ₁ duration + (1 + G1 duration subject) + (1 + G1 duration item)	10	10491	-5234.3	0.86	0.35

Table 3: Temporal coordination – Nested model comparison.

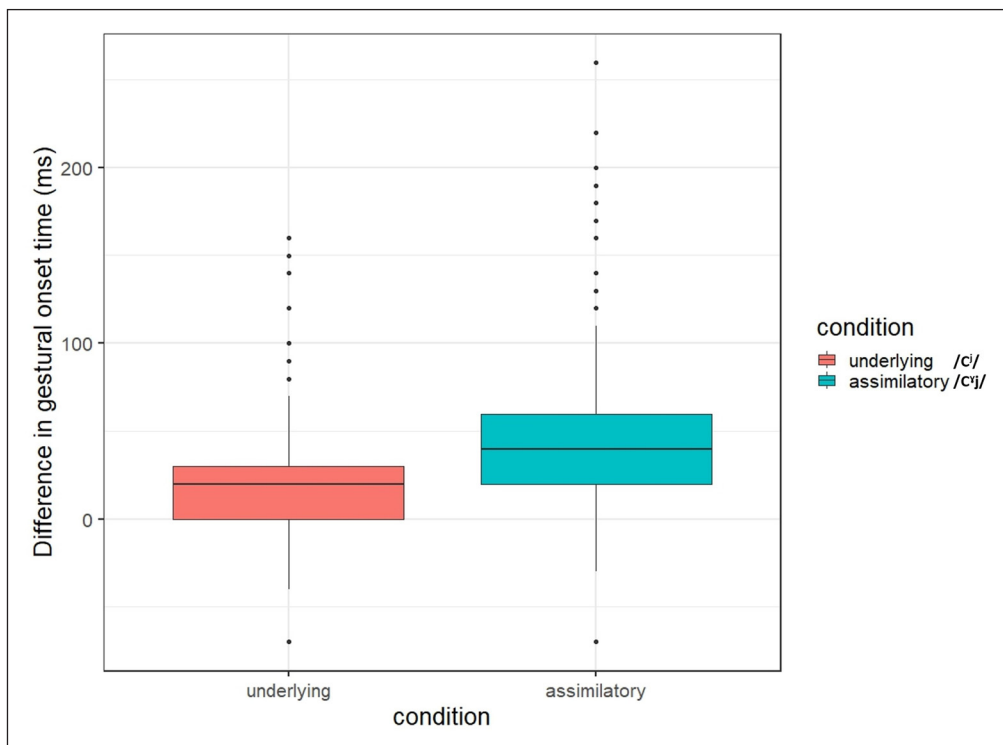


Figure 10: A boxplot of onset-to-onset lag across *Condition*.

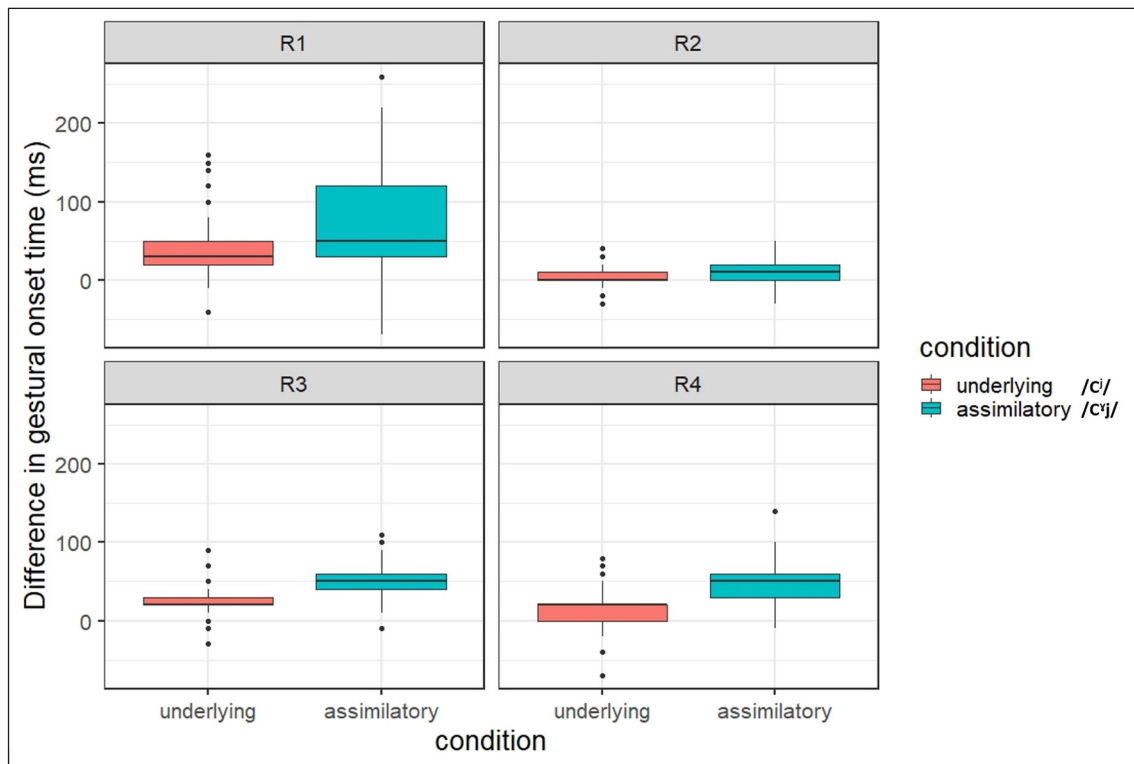


Figure 11: A boxplot of onset-to-onset lag across *Condition* for each speaker.

In summary, ASSIMILATORY palatalization exhibits a longer onset-to-onset lag than UNDERLYING palatalization. This suggests a delayed onset of the palatal gesture for ASSIMILATORY palatalization as compared to UNDERLYING palatalization. Crucially, however, the longer onset-to-onset lag observed in ASSIMILATORY palatalization does not correlate with an increase in G1 duration. That is, for both UNDERLYING and ASSIMILATORY palatalization, there is no clear correlation between G1 duration and onset-to-onset lag, showing the temporal coordination of complex segments. This contrasts with past work showing that segment sequences show a strong correlation between these measures (see **Figure 1**). The crucial null effect of *G1 duration* indicates that both UNDERLYING and ASSIMILATORY palatalization are consistent with the temporal coordination of complex segments.

4.3. Articulatory evidence of incomplete neutralization

Figure 11 shows the normalized longitudinal position (front-back) of the TB sensors at the gestural onset across conditions. Positive and negative values on the y-axis illustrate the frontness and backness of the tongue body, respectively. The spatial position of the TB is more retracted for the ASSIMILATORY palatalization (e.g., /bʲ + j/) than for the UNDERLYING palatalization (e.g.,

/bʲ/) at the onset of the palatal gesture. As shown in **Figure 13**, this pattern is consistent across speakers (see the medians in the box plots).

To assess the statistical significance of the trends in **Figure 12** and **Figure 13**, we fit a series of linear mixed-effects models to the data (for additional detail, see Section 3.4). As shown in **Table 4**, the addition of *Condition* improves the baseline model, which contains only random effects of subject and item ($\chi^2 = 4.4$, $p = 0.03$), indicating that the TB position significantly differs by *Condition*.

In the best-fitting model for temporal coordination (TB position \sim *Condition* + (1 + condition|speaker) + (1 + condition|item)), the main effect of *Condition* is marginally significant ($t = -2.4$, $p = 0.076$). Specifically, the TB is estimated to be 1.3 mm more retracted for the ASSIMILATORY palatalization than for the UNDERLYING palatalization at the onset of the palatal gesture. This difference is consistent with the presence of a secondary tongue dorsum retraction gesture for plain stops. Some residue of velarization for plain stops persists in the ASSIMILATORY condition, in line with the previous observations of an active tongue dorsum retraction gesture in the “plain” stop series.

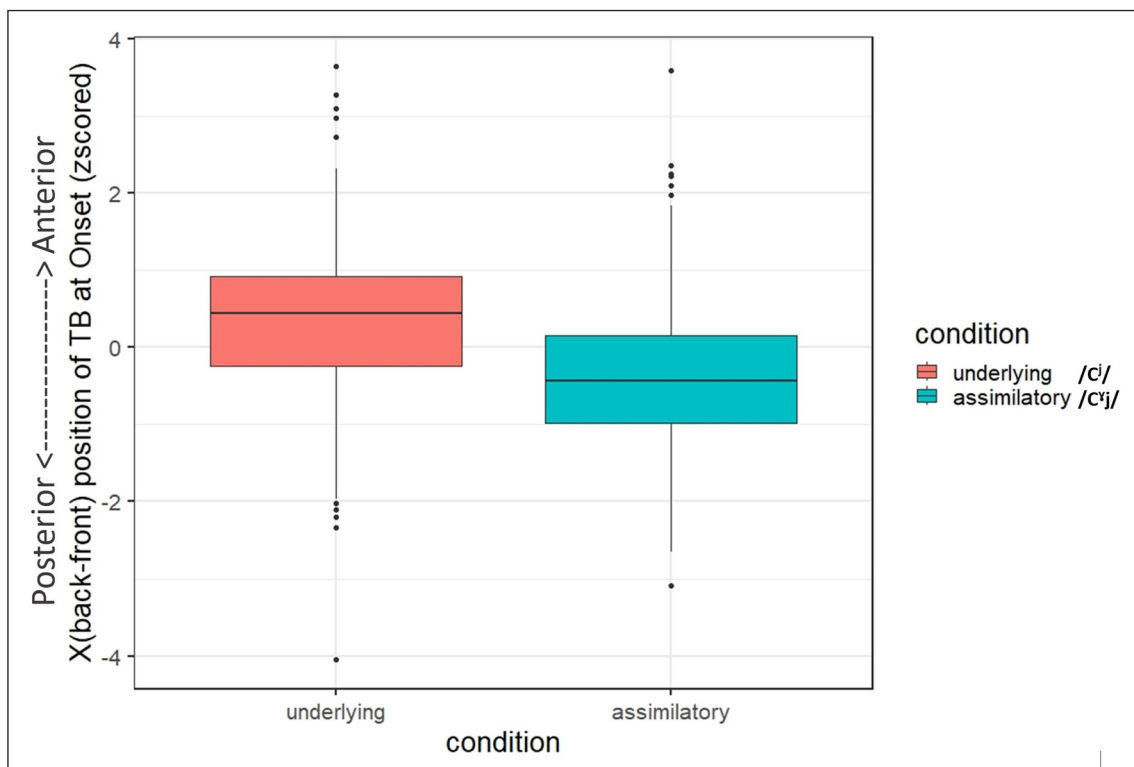


Figure 12: A boxplot of TB position (z-scored) at palatal gesture onset.

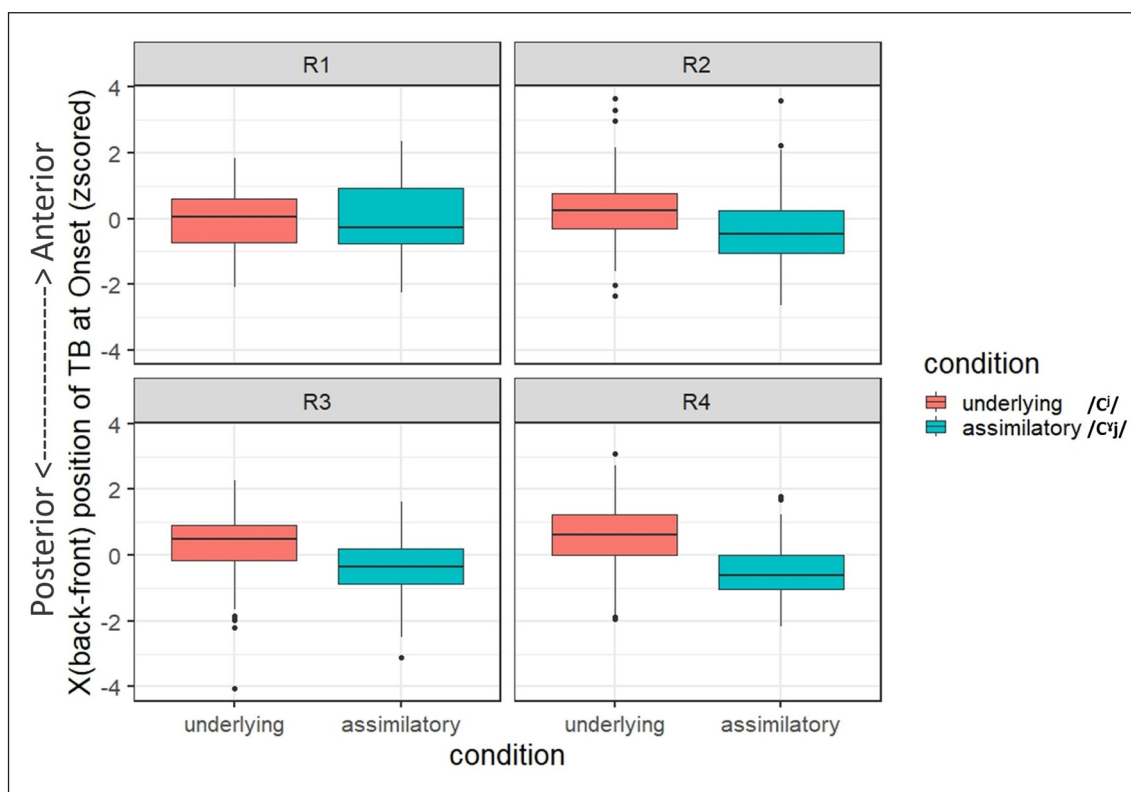


Figure 13: A boxplot of TB position (z-scored) at palatal gesture onset for each speaker.

TB	Df	AIC	logLik	χ^2	$\Pr(>\chi^2)$
1 + (1 + condition speaker) + (1 + condition item)	8	4575.8	-2279.9	NA	NA
1 + condition + (1 + condition speaker) + (1 + condition item)	9	4573.4	-2277.7	4.4	0.03

Table 4: TB position – Nested model comparison.

5. Discussion

5.1. Overview

Incomplete neutralization has been the focus of much work in laboratory phonology and phonetics. Phenomena which have been described as neutralization have often turned out to show phonetic traces of underlying contrasts. Final devoicing is perhaps the most well-studied case, but there are numerous others, as well as some cases of complete neutralization (see references in the introduction). Determining neutralization status requires careful examination of the phonetic record.

In the present study, we explored a case of putative phonological neutralization, that of palatalized consonants (underlying palatalization; e.g., /bʲ/) and plain consonants preceding a palatal glide (assimilatory palatalization; e.g., /b + j/) in Russian. The purpose of this study is to explore how palatalization of plain consonants preceding a palatal glide (assimilatory palatalization) is phonetically different from underlyingly palatalized consonants (underlying palatalization). To do so, we conducted an EMA experiment and examined the temporal coordination and the spatial positions of articulators involving underlying and assimilatory palatalization in Russian.

We asked two research questions as follows: (1) Do underlying palatalization (e.g., /bʲ/) and assimilatory palatalization (e.g., /b + j/) exhibit temporal coordination characteristic of complex segments? (2) Do underlying palatalization (e.g., /bʲ/) and assimilatory palatalization (e.g., /b + j/) exhibit spatial and/or temporal differences? The first research question was regarding whether two cases of Russian palatalization show neutralization. The second research question was regarding whether the neutralization is complete. Regarding the first question, for there to be evidence of neutralization, both the underlying and assimilatory palatalization should exhibit no correlation between consonant duration and onset-to-onset lag. With regard to the second question, for there to be evidence of incomplete phonetic neutralization, there should be significant spatial and/or temporal differences. Given that plain consonants have secondary velarization (Litvin, 2014; Roon & Whalen, 2019; Skalozub, 1963), we predicted that the gestural blending of two secondary articulation gestures (palatalization and velarization) in assimilatory palatalization would lead to incomplete neutralization of underlying and assimilatory palatalization in Russian. A key finding from the EMA study is that both underlying and assimilatory palatalization types were consistent with being complex segments, according to the hypothesized temporal basis of complex segments (Shaw et al., 2021). Evidence for the coordination pattern came from the relation between G1 duration and onset-to-onset lag. Specifically, these intervals were statistically independent for both underlying and assimilatory palatalization types. The onset of the palatal gesture, G2, was unaffected by the duration of G1, indicating that G2 movement is coordinated with the beginning of G1. The gestures for both underlying and assimilatory palatalization types are consistent with being coordinated as complex onsets. This suggests that the contrast between a palatalized consonant and a plain consonant is neutralized to the palatal counterpart when a plain consonant is followed by a glide.

However, underlying and assimilatory palatalization do show significant phonetic differences in other dimensions. The onset lag is longer for the assimilatory palatalization than for the underlying palatalization. Furthermore, the spatial position of the articulators also provided residual evidence of an underlying tongue dorsum retraction for assimilatory palatalization. In particular, the spatial position of the TB at the onset of the palatal gesture was more retracted for

the assimilatory palatalization condition than for the underlying palatalization condition. This is in line with previous findings of Russian plain consonants having secondary velarization, and may in fact be underlyingly velarized, /C^v/ (Padgett, 2001; Rubach, 2000). That is, velarized consonants preceding a palatal glide (assimilatory palatalization) undergo palatalization while exhibiting a small residue of velarization e.g., /b^v+j/ → [bj]). As predicted in Section 2, the gestural overlap on the same tract variable (i.e., palatalization vs. velarization) would lead to gestural blending between these two gestures. Accordingly, this results in a slightly more retracted tongue position for the assimilatory palatalization compared to underlying palatalization, which only has the palatal gesture on the TB tract. This is in line with the previous acoustic finding of consonant-glide sequences (C+j) in Russian exhibiting significantly higher F2 at the transition onset than palatalized consonants (C') (Diehm, 1998). Consequently, this difference leads to incomplete neutralization between the underlying and assimilatory palatalization in Russian.

Previous studies have shown that Russian listeners are sensitive to the contrast in perception (Diehm, 1998, Babel & Johnson, 2007). The current study found that palatalized consonants derived from C+j sequences (assimilatory palatalization) are phonetically different from underlyingly palatalized consonants (underlying palatalization). However, it is worth noting that this may not be the main perceptual cue to the contrast between consonant-glide sequences (C+j) and palatalized consonants (C'), as plain consonants preceding a palatal glide are also palatalized. That is, Russian listeners don't necessarily need to perceive this particular difference between palatalized consonants (C') and consonant-glide sequences (C+j) per se, because they can rely on other phonetic cues. For example, the glide in C+j sequences is longer than the off-glide in palatalized consonants and the glide in C+j sequences exhibit a higher F2 as compared to palatalized consonants (Diehm, 1998; Ladefoged & Maddieson, 1996; Suh & Hwang, 2016). In addition, Kochetov (2006b) as well as the current study has shown that consonant-glide sequences exhibit a longer palatal gesture in comparison to palatalized consonants. However, these more salient acoustic cues do not necessarily determine whether the plain consonant in the consonant-glide sequences is palatalized or not. In the current study, we devised a diagnostic to measure palatalization by assessing the temporal and spatial coordination of gestures involving underlying and assimilatory palatalization in Russian.

Although we focused on the C+j sequence to examine assimilatory palatalization, this case is part of a larger process of C + palatal(ized) segments in Russian. That is, "plain" consonants tend to undergo palatalization when followed by any palatal or palatalized consonant (e.g., Timberlake, 2004). For example, /s/ in the word 'campfire' /k^vo^ls^vt^ʃor^v/ is also realized as [s^j], resulting in [k^vΛ^ls^ʃt^ʃor^v] (cf. [k^vΛ^ls^vt^vr^vʃ] 'campfire (pl)'). Furthermore, though assimilatory palatalization in C+C' sequences is beyond the empirical scope of this study, we predict that the target consonant in such cases would phonetically behave similarly to the target consonant in C+j sequences. For

example, if we examine /s/ preceding /tʲ/ (C + Cʲ sequence of assimilatory palatalization) and compare it with underlying palatalization (e.g., /sʲ/), we also expect incomplete neutralization between them. That is, /sʲ/ preceding /tʲ/ will also exhibit the temporal coordination of complex segments, while showing residual tongue dorsal retraction (i.e., /sʲtʲ/ → [sʲtʲ]).

5.2. Incomplete neutralization as gestural overlap

Incomplete neutralization has been the focus of much work in phonology as well, since it has been argued that it is difficult to incorporate incomplete neutralization into models of the grammar (e.g., Braver, 2019; Brockhaus, 1995; Dinnsen & Charles-Luce, 1984; Ernestus & Baayen, 2007; Piroth & Janker, 2004; Port & O'Dell, 1985; Roettger et al., 2014; Van Oostendorp, 2008). For example, in some serial/rule-based models, a phonological rule has to be applied before low-level phonetic implementation rules. However, if final devoicing (the phonological rule) is applied first, it is impossible to apply the phonetic implementation rules, since the voicing contrast has already been neutralized. To solve this issue, previous studies have proposed a number of solutions, such as applying phonetic implementation rules before or simultaneously with phonological rules (Dinnsen & Charles-Luce, 1984; Port & O'Dell, 1985; Slowiaczek & Dinnsen, 1985), or even without posting changes to rule ordering. For example, some researchers have argued that incomplete neutralization is driven by hypercorrection of orthographic cues in the service of communicative goals (e.g., Fourakis & Iverson, 1984; Iverson & Salmons, 2011; Jassem & Richter, 1989; Mascaró, 1987; Piroth & Janker, 2004; Warner et al., 2004), while others have proposed that incomplete neutralization reflects fine-grained phonetic information in the mental lexicon (Alegre & Gordon, 1999; Baayen et al., 1997; Bybee, 1994; 1995; 2001; Ernestus & Baayen, 2007; Roettger et al., 2014). Most recently, Du and Durvasula (2022) have argued that the source is actually outside the phonology proper, and stems from planning.

However, the current study approaches incomplete neutralization with a different perspective and shows that at least some cases of incomplete neutralization can be modeled as gestural overlap and blending. From the EMA data, we found residual evidence of an underlying tongue dorsum retraction in the assimilatory palatalization condition. This finding is in line with the prediction made in Section 2. That is, the gestural overlap resulting in gestural blending of two secondary articulation gestures (palatalization and velarization) leads to incomplete neutralization of underlying and assimilatory palatalization in Russian. This process also fits in with other empirical cases, such as vowel assimilation in Igbo (Zsiga, 1997) and blended vowels in Romanian (Marin, 2012).

In Igbo, when a vowel is followed by another vowel, the preceding vowel is assimilated to the following vowel (i.e., complete assimilation: V1V2 → V2V2). For example, /e/ in /nwoke a/ 'this man' is assimilated to the following vowel /a/ (i.e., /nwoke#a/ → [nwoka#a]). However, previous studies have reported such vowel assimilation exhibits gradient behavior (Clark, 1990;

Emenanjo, 1978; Zsiga, 1997). For example, for /nwoke#a/, the realization of /e/ is different from a typical vowel realization, as the realization of /e/ varies from more [e]-like realizations to more [a]-like realizations. Zsiga (1997) argued that this is due to the shortening of V1 in the word final position and compensational lengthening of V2. Zsiga rejected the gestural blending account “because it fails to link assimilation to final reduction.” However, it may be possible to link assimilation to final reduction in the AP framework, if we assume that weaker blending strength contributes to reduction. When V1 occurs at the word-final position, where vowels are reduced, the blending strength of V1 is also reduced. This proposal involves a dependency between blending strength and word position. Introducing this type of dependency makes it possible to describe Igbo vowel assimilation in terms of blending between two gestures V1 and V2, with varying degrees of overlap between the two gestures. For example, for /nwoke#a/, the blending strength of /e/ is weaker than that of /a/, as /e/ occurs at the word-final position. When there is less or no overlap between two vowels, /e/ is realized more like [e]. On the other hand, when the two vowels significantly overlap, the realization is more like [a], as the blending strength for /a/ is stronger. However, the [a]-like realization is expected to be different from a typical /a/ vowel, as it comes from the blending of two vowels.

Marin (2012) also proposed a production model to examine the incomplete neutralization of Romanian vowels. In Romanian, the diphthong /ea/ is realized as [e] in an unstressed syllable (derived [e]), and previous acoustic studies (e.g., Marin, 2005) revealed that the derived [e] is significantly more central than the vowel [e] that is underlyingly /e/ (underived [e]). She hypothesized that it might be attributable to different production mechanisms between derived and underived [e], and tested her hypothesis by comparing acoustic data to model simulations. Using an articulatory based synthesizer, *TADA* (*Task Dynamic Application*; see e.g., Nam et al., 2006), the underived /e/ was modeled with the gestural specifications of a single gesture [e], while the derived [e] was modeled as the blending of two gestures /e/ and /a/, reflecting its underlying status as a diphthong. The results revealed that the blending of two gestures /e/ and /a/ showed similar acoustic properties to a naturally produced derived [e], and simulations of underived [e] were also similar to a naturally produced underived [e]. Along with our findings, Marin’s results also support that at least some cases of incomplete neutralization can be modeled as gestural overlap and blending.

5.3. Alternative account: The effect of back vowels on tongue body position

The present study has demonstrated that incomplete neutralization might be attributable to two secondary articulation gestures (palatalization and velarization) in assimilatory palatalization. However, there is an alternative explanation for the retracted tongue position observed as a result of this process. Namely, it is possible that the retracted tongue position is attributable to the blending of the palatal gesture and the following vowel gesture.

Vowel-to-consonant coarticulation is commonly found crosslinguistically, such as in English (e.g., Keating, 1993), Russian (e.g., Iskarous & Kavitskaya, 2010), French (e.g., Guitard-Ivent, Turco, & Fougeron, 2021), Catalan (e.g., Recasens, 1985), and Algerian Arabic (e.g., Bouferroum & Boudraa, 2015). Given that the target vowels are all back vowels (/u/ and /o/) in the experiment, the retracted tongue position of the assimilatory palatalization could be the result of blending the palatal gesture and the back vowel gesture. For this to be a viable alternative, we would also have to consider how the vowel is coordinated with the other gestures in our target items. For predictions about gestural phasing patterns between consonants and vowels, we turn to the coupled oscillator model of syllable structure.

The coupled oscillator model seeks to explain the observations that syllable structure is associated with a characteristic pattern of temporal coordination (Goldstein, Byrd, & Saltzman, 2006; Goldstein, Nam, Saltzman, & Chitoran, 2009; Nam, Goldstein, & Saltzman, 2009; Saltzman, Nam, Krivokapić, & Goldstein, 2008). To explain observed overlap between onset consonants with the following vowel, it is hypothesized that a gesture in a syllable onset is coordinated in-phase with the following vowel. The implication is that the two gestures are triggered at the same time. In contrast, a coda gesture is hypothesized to be coordinated anti-phase with the preceding vowel, showing a sequential timing between the two gestures. Furthermore, the coupled oscillator model hypothesizes that multiple gestures in a syllable onset are coupled anti-phase with each other, along with both being in-phase with the vowel. To satisfy this competitive coupling demand, one gesture (C1) shifts away from the vowel, and the other gesture (C2) shifts toward the vowel. Consequently, for gestures in the syllable onset position, the midpoint of prevocalic consonants exhibits a stable timing with the following vowel, regardless of the number of onset consonants. This pattern, the so-called “c-center effect”, has been observed in several studies (Browman & Goldstein, 1988; 2000; Crouch, Katsika, & Chitoran, 2020; 2022; Goldstein et al., 2007; Goldstein, Chitoran, & Selkirk, 2007; Marin, 2013; Marin & Pouplier, 2010; Nam & Saltzman, 2003; Shaw & Gafos, 2015; Sotiropoulou & Gafos, 2022).⁵

The differences in TB position observed across palatalization conditions, which we attributed to incomplete neutralization, might instead be attributable to a different vowel coordination pattern between underlying and assimilatory palatalization. For underlying palatalization (e.g., /b^hus^vt^v/ [b^hus^vt^v]), the labial and palatal gestures might be coupled in-phase with each other and also coupled in-phase with the vowel. Due to these coupling relations, the labial and palatal gestures will start at the same time with the following vowel. In contrast, for assimilatory palatalization (e.g., /b^vjut^v/ [b^vjut^v]), the labial and palatal gestures might be competitively coupled with the

⁵ Not all languages with complex syllable onsets show the c-center effect. Brunner et al. (2014) show that some German clusters do not show the c-center effect, although they show other indices consistent with global timing (Sotiropoulou & Gafos 2022). Georgian consonant clusters also do not show the c-center effect, possibly due to reasons related to the morphology of the language (Crouch et al., 2020, 2022, c.f., Goldstein et al. 2007).

vowel (i.e., coupled anti-phase with each other, and also coupled in-phase with the following vowel). Due to this competitive coupling, the vowel gesture for /u/ would start before the palatal gesture and continue concurrently during the palatal gesture. In both cases, the temporal overlap between the palatal gesture and the following vowel gesture in the same tract variable (TB) will lead to gestural blending between them. Crucially, however, when the spatial position of the TB gestures is compared at the onset of the palatal gesture, there may be differences, owing to the differences in temporal coordination. Assimilatory palatalization, which has the tongue backing for /u/ starting earlier than the palatal gesture, will show a more retracted tongue position than the underlying palatalization condition, since the backing movement for /u/ will have already started before the palatal gesture starts, just in the assimilatory palatalization condition. That is, due to the existence of the vowel gesture preceding the palatal gesture for the assimilatory palatalization, the gestural blending of the tongue backing for /u/ and the fronting for /j/ may result in a more retracted tongue position at the onset of the TB gesture for the assimilatory palatalization as compared to the tongue position for the underlying palatalization. This is a reasonable alternative that is compatible with both the temporal basis of complex segments and the coupled oscillator model of syllable structure.

Other aspects of our data serve to rule out this alternative hypothesis. Crucially, if the labial gesture and the palatal gesture are coordinated anti-phase in the assimilatory palatalization condition, similar to segment sequences in English such as /bjut/ ‘butte’ (Shaw et al., 2019; Shaw et al., 2021), they are expected to result in the temporal coordination of segment sequences, which is not the case in our data (**Figure 9**). Consequently, the back vowel is less likely to be the source of incomplete neutralization. C-center timing treats the consonantal gestures as separate segments (timed anti-phase) and is therefore incompatible with complex segment coordination. Thus, while the difference in tongue position at the onset of the palatal gesture is consistent with c-center timing, the data on the whole is not.

5.4. Does the delayed onset of the palatal movement also follow from blending?

As discussed above, gestural blending between palatalization and velarization in the assimilatory palatalization condition may lead to a more retracted tongue position than would be expected for underlying palatalization. However, it is not clear what causes the delayed onset of the tongue body movement associated with the palatal gesture in the assimilatory palatalization condition. Here, we consider whether gestural blending could indirectly condition this difference, or, alternatively, whether some other parameter is responsible. In all we consider three possible explanations.

The most parsimonious explanation would be if the gestural blending parameters posited to explain the spatial differences across conditions could also account for the temporal difference. In the AP framework, the blending of the dynamical parameters of two gestures is predicted

to produce an outcome that falls somewhere in-between the two gestures, depending on the blending strength of the two gestures in question (e.g., Browman & Goldstein, 1989; 1992). We first consider the possibility that the tongue body gesture starts at the same time for both palatalization conditions, but that blending delays the detection of the movement onset in the assimilatory palatalization condition. We explored this possibility through simulation in TADA; however, we found that varying the gestural blending strength alone was insufficient to derive differences in onset lag. Detection of gestural onsets, using our methods (see Section 3.4) is sensitive to the stiffness of the gestures but not to blending strength. Thus, at least in the version of AP implemented in TADA, blending strength alone cannot account for the difference in onset lag across conditions.

A second possible explanation is to posit that, in the assimilatory palatalization condition, the labial and palatal gestures are coordinated anti-phase, and the labial and velar gestures are coordinated in-phase. In the underlying palatalization condition, by contrast, the labial and palatal gestures are coordinated in-phase. Such a coordination difference will result in the delayed onset of the TB gesture in the assimilatory palatalization condition relative to the underlying palatalization condition. The delay of the TB gesture will generate a delay in movement onset, similar to that observed in our data. However, this leads to the same problem as the competitive coupling account discussed above in Section 5.3. The anti-phase coordination between the gestures for /b/ and /j/ is expected to produce a positive correlation between C1 and onset-to-onset interval, the temporal coordination pattern characteristic of segment sequences. As we noted, this is not the case for assimilatory palatalization in Russian. The increased onset-to-onset lag emerges alongside evidence for complex segment (as opposed to segment sequence) coordination.

Lastly, we consider the possibility that in assimilatory palatalization the velar gesture starts before the palatal gesture and continues concurrently. On this proposal, the labial and palatal gestures are still coordinated in-phase, the coordination relation for complex segments. This gets around the problems of other approaches by successfully deriving the observed relation between C1 duration and onset-to-onset lag (**Figure 9**). However, in order to derive the differences across conditions, the velar gesture is eccentrically timed to the palatal gesture so as to start slightly earlier in time. Eccentric timing refers to phasing relations that are neither in-phase nor anti-phase and have been argued to be empirically necessary in some languages (e.g., Goldstein, 2011; Geissler et al., 2021). In this case, eccentric timing can derive delayed onset of the TB movement for the assimilatory palatalization while maintaining the temporal coordination of complex segments. Of the three theoretical possibilities, the first two are perhaps more parsimonious, in that they draw on already well-established principles, but only the third derives the complete range of empirical facts. Notably, none of these accounts requires any special mechanisms for incomplete neutralization per se. Patterns of incomplete neutralization emerge from the space of parameters used to model natural speech production in Articulatory Phonology.

5.5. Conclusion

Russian contrasts palatalized and non-palatalized (plain or velarized) consonants, but this contrast is reported to be neutralized when a plain consonant is followed by a palatal glide or a palatal consonant (e.g., Avanesov, 1972; Timberlake, 2004). In this paper, we used Electromagnetic Articulography (EMA) to explore the neutralization of palatalized consonants (underlying palatalization; e.g., /bʲ/) and velarized consonants preceding a palatal glide (assimilatory palatalization; e.g., /bʲj/).

A key finding from the EMA experiment is that both underlying and assimilatory palatalization exhibited temporal coordination characteristic of complex segments, showing no correlation between consonant duration and onset-to-onset lag. This suggests that the contrast between a palatalized consonant and a velarized consonant is neutralized to the palatal counterpart when a velarized consonant is followed by a glide. However, the neutralization of the secondary articulation contrast is phonetically incomplete. In particular, we found that the tongue body was significantly more retracted for the assimilatory palatalization than for the underlying palatalization at the onset of the palatal gesture. The difference across conditions was small (1.3 mm) but consistent across speakers. In addition, *Onset-to-onset lag* is significantly longer (25 ms) for assimilatory palatalization than for underlying palatalization. These significant differences suggest that the neutralization of the palatalized-velarized contrast is phonetically incomplete. Furthermore, the residual evidence of an underlying tongue dorsum retraction for the assimilatory palatalization is in line with previous findings of Russian non-palatalized consonants having secondary velarization.

Incomplete neutralization has been argued to be a serious challenge to models of the phonology-phonetics interface, particularly those that deal with the neutralization component in terms of symbol substitution. The current study offers an explanation for incomplete neutralization patterns by showing that at least some cases of incomplete neutralization can be modeled as gestural overlap and blending in the Articulatory Phonology framework. There is substantial potential for the gestural overlap account to generalize across a wide range of incomplete neutralization cases.

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Competing Interests

The authors have no competing interests to declare.

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