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PHONOTACTIC AND MORPHONOTACTIC INFLUENCES ON THE (A)SYNCHRONICITY OF CONSONANT CLUSTERS IN POLISH

Keywords: Polish phonotactics, morphonotactics, EMA, cluster synchronicity, Net Auditory Distance

Abstract

A pilot speech production experiment combined articulatory data obtained using Electromagnetic Articulography (EMA), along with acoustic measures, to investigate the effects of cluster size (CC vs. CCC) and morpheme boundaries on consonant cluster synchronicity for five speakers of Polish. We found that being placed in a larger cluster leads to less synchronous productions of two-consonant sequences. We also found, surprisingly, greater synchronicity for clusters spanning a morpheme boundary than for the same cluster within a morpheme. Our findings may be interpreted from a listener-oriented perspective in which speech production is sensitive to perceptual considerations.

1. Introduction

In research on consonant cluster phonotactics, we can identify a number of distinct areas of investigation, which the present paper will attempt to bring together. One of these is the question of markedness vs. well-formedness of given phonotactic patterns, with particular attention to consonant clusters. Explanatory models of phonotactics most often refer to the syllable as the domain of phonotactic constraints defining the "goodness" of clusters. The most well-known model relies on the Sonority Sequencing Principle (e.g. Hooper 1976; Selkirk 1984; Parker 2002), sometimes enhanced by syllable structure and contact laws (Vennemann 1988). In this approach, appropriate sonority contours and sonority distances between consonants are said to characterize unmarked, well-formed consonant sequences. For example, a stop-approximant onset cluster, as in e.g. English *quite* /kwaɪt/, would qualify as a "good" initial sequence. An alternative approach, referred to as Net Auditory Distance (NAD; Dziubalska-Kołaczyk 2014) rates phonotactic well-formedness without reference to the syllable, but includes place of articulation in its calculations. Thus, NAD would make a distinction between stop-approximant clusters with the same and different places of articulation – the latter would be preferred (e.g. /kw/ is preferred over /pw/). Notably, unlike approaches based on sonority, the NAD formula also allows for a straightforward evaluation of consonant clusters with more than two members, the effects of which are of interest for the present study.

An additional issue with regard to cluster well-formedness concerns the effects of morpheme boundaries. Morphonotactics is "the area of interaction between morphotactics and phonotactics" (Dressler and Dziubalska-Kołaczyk 2006: 250). Clusters are either purely phonotactic, i.e. morpheme-internal, or morphonotactic, i.e. resulting from morphological operations. Morphonotactic clusters are expected to be longer and phonologically more marked than phonotactic ones. Their relative markedness serves often as a cue signalling morphological meaning. In some cases, the same cluster may belong to both subtypes – it may or may not span a morphological boundary. The effects of morpheme boundaries on cluster pronunciation are of interest for the present study.

Beyond the question of well-formedness, an additional focus is the degree of phonetic coordination underlying different phonotactic patterns. That is, previous research has sought to quantify the degree to which consonant clusters are articulated synchronously, and the degree of synchronicity between consonants in a cluster and neighbouring vowels. Many studies investigating this issue have employed electromagnetic articulography (EMA) to test phonological hypotheses about syllable structure. This research has operationalized its hypotheses with two kinds of metrics: in one approach, articulatory lags between various cluster landmarks and so called "anchors" in the following vowel are used to determine whether pre-vocalic consonants form a "complex" onset (e.g. Shaw et al. 2009). In another approach, cluster "synchronicity", i.e. the time lags between consonantal gestures (Hermes et al. 2017; Pouplier et al. 2020), sheds light on prosodic aspects of phonotactics, without making any a priori assumptions about the syllable as a phonological primitive. Since we are sceptical about the syllable, we believe that cluster synchronicity is an appropriate metric for operationalizing the effects of cluster size and morpheme boundaries on cluster production.

In this paper, we offer a pilot EMA study of consonant clusters in Polish, investigating the interaction between the phonetic properties of cluster production with cluster size, as well as the interaction of cluster pronunciation with the presence of morpheme boundaries. To our knowledge, neither of these interactions in Polish has been the subject of experimental phonetic study.[1] The first interaction sheds light on the question of whether C1 and C2 in a cluster are pronounced more synchronously as a function of whether the cluster is pre-vocalic, or whether the C1–C2 sequence is embedded in a larger cluster (e.g. /kr/ in *kryć* /krɨt͡ɕ/ 'cover' vs. /kr/ in *krwi* /krvi/ 'blood (genitive singular)'.[2] The second interaction compares the same two-member clusters as a function of whether they span a morpheme boundary (e.g. /sp/ in *spoza* /s+pɔza/ 'from beyond' vs. *spoko* /spɔkɔ/ 'cool, relax'). In both cases, we investigate the relative degree of phonetic synchronicity of the two consonants in the cluster (the first two of three in the case of CCC onsets), using articulatory and acoustic data.

2. Background – cluster (a)synchronicity in Polish

Available phonetic evidence suggests that onset clusters in Polish are produced in a relatively asynchronous manner. This is particularly true in comparison to English, in which evidence for synchronous production of onset clusters may be found both in textbook descriptions of the language, as well as experimental phonetic data. Notably, English pronunciation textbooks (e.g. Cruttenden 2014; Carley and Mees 2020) describe robust allophonic processes induced by synchronous onset clusters, including approximant devoicing (e.g. *clear*, *please*), affrication (e.g. *trip*, *drip*), and j-coalescence (*tune*, *duration*). The articulatory synchronicity underlying these processes in English has been confirmed experimentally using EMA (see Marin and Pouplier 2010). In textbook descriptions of Polish (Dukiewicz and Sawicka 1995), such processes are not attested.[3]

1 The only study we have found is a conference presentation by Ćavar et al. (2023), which looked at patterns of assimilation of coronal-coronal sequences as a function of boundary strength. This study is discussed briefly in section 4.

2 A reviewer takes issue with this pair of examples on the basis of voicing, pointing out that the /r/ in *krwi* can be devoiced. This question is orthogonal to the question we are interested in, namely the temporal coordination of supra-laryngeal articulators including the lower lip, tongue tip, and tongue body, which are independent of the larynx. In the data presented in section 3, other pairs, in which voicing is consistent, behave similarly to this pair.

3 One might ask whether approximant devoicing in English is induced by aspiration of initial stops, which is absent from Polish according to most descriptions, rather than consonant timing. Aspiration combines with consonant timing to induce the process; it does not rule out timing as an explanation. Indeed, some degree of synchronous cluster production is an obvious prerequisite for the stop to induce devoicing – in asynchronous productions voicing

More recent experimental studies of Polish have documented the asynchronous nature of Polish onset clusters. An acoustic study by Święciński (2012) revealed asynchronicity in C^j/Cj onsets, providing evidence for the presence of a true glide in words such as *piasek* 'sand'. In other words, what is often described as a single palatalized consonant appears to be a two-consonant sequence, in which C2 is identifiable as a separate phonetic entity. Meanwhile, an articulographic study by Hermes et al. (2017; see Fig. 17) revealed large target-to-target lags in pre-vocalic clusters in Polish. Additionally, an acoustic study by Schwartz (2022a) revealed VOT measurements for the voiceless stop in s-stop onsets that were comparable to those for singleton voiceless stops, suggesting greater separation between the sibilant and the stop than is found in English, which is known for VOT shortening in this context (Cho et al. 2014). Finally, an EMA study by Schwartz et al. (2021) compared target-to-target lags produced by Polish-English bilinguals in the "same" clusters in both their languages. That study revealed larger lags for Polish TR (stop-approximant) onset clusters.

While the above discussion provides insight into how the same clusters are produced in Polish relative to other languages, there are additional conditions in Polish which may have an influence on cluster production. In this paper we investigate two such conditions in a pilot EMA study. The first condition concerns the size of the cluster. In other words, will two consonants be pronounced more or less synchronously as a function of whether they appear before a vowel or before another consonant? The second concerns the question of morpheme boundaries. That is, what effects, if any, will the presence of a morpheme boundary between the consonants have on the phonetic synchronicity of the consonant sequence? In line with other work based mainly on English, we might expect morpheme boundaries to be associated with greater phonetic separation of the consonants in the boundary-spanning cluster. For example, Smith et al. (2012) found that prefixes in words like *mistimes* induced longer VOT of /t/ than in in monomorphemic *mistakes*, alongside other phonetic differences in the initial /mɪs/ sequence.

3. Method

A Carstens AG501 electromagnetic articulograph (EMA), housed in the phonetics laboratory of a German University, was employed for the study. Articulatory data was gathered from five native speakers of Polish (1F, 4M, median age 32). The speakers all had a very high level of proficiency in English, and some knowledge of other languages. For this reason, after sensors were put in place, on the lower lip, tongue tip, tongue blade, and tongue body, and before the Polish recordings began, each speaker engaged in a five-minute conversation, in Polish, in order to mitigate possible effects of language mixing (e.g. Grosjean 1998).

will start simultaneously with the approximant, regardless of the length of VOT. For example, a code-switching study of Polish learners of English by Cieślak (2015) induced aspiration in the participants' L1 Polish, but did not induce approximant devoicing. See Schwartz (2022b) (Fig. 2), for an illustration.

The experimental items included three pairs of words in which the same two-consonant sequence was found in either a two-member or three-member onset cluster (e.g. /kr/ in *kryć* /krɨt͡ɕ/ 'cover' vs. *krwi* /krvi/ 'blood (gen sg)'), and four pairs of words in which the same onset cluster either spans a prefix-stem boundary, or appears within a single morpheme (e.g. /sp/ in *spoza* /s+pɔza/ 'from beyond' vs. *spoko* /spɔkɔ/ 'cool, relax'). The experimental items were placed in a carrier phrase *powiedziała X jeszcze raz* 'she said X one more time', in pseudo-randomized order along with an additional series of CVC-initial and cluster-initial words used for different experiments. Two repetitions were made of each item.

Before continuing, it is worth commenting on the relatively small amount of data described in this paper. First and foremost, this is a function of EMA. Due to the invasive nature of the method (sensors are glued to the various parts of the tongue and lips), and the preparations (sterilization, calibration, sensor placement, etc.) that need to be made for each speaker, EMA experiments typically are based on a very small number of participants (see Rebernik et al. 2021 for discussion of limitations involved with EMA studies). The present study is based on data from five speakers. Additionally, since EMA experiments can be tiring for participants, and our recording session included items for other experiments with different research questions, only a small number of CC vs. CCC (six target words) and phonotactic vs. morphonotactic (eight words) pairs were included. Other publications describing EMA experiments are based on similarly small numbers of speakers and items. For example, Hermes et al.'s (2017) EMA study of Polish was based on eight target words produced by three speakers.

A script written in R (R Core Team 2021) was used to import articulatory data, in parallel with the audio recordings, into the EMU Web App for annotation. In the annotation phase, tracks of vertical position, velocity, and acceleration of the EMA sensors were consulted in order to mark the following articulatory events: onset of gesture, peak velocity of gesture, target of gesture. Segmental and word boundaries were also marked in the acoustic signal. An additional R script was used to extract the annotated sound files into a spreadsheet suitable for analysis.

Results from four measures were analysed. The first was an articulatory measure, target-to-target lag (t2t), defined as the duration of the time window between C1 and C2 gestural targets (vertical position maxima). A normalized lag measure (t2t/V), was obtained by dividing by the duration of the following vowel. An illustration of the t2t measure is provided in Fig. 1, which shows an acoustic waveform and spectrogram of Polish *krwi* /krvi/ 'blood (genitive singular), articulatory position tracks of the tongue tip, lower lip, and tongue body. A selection has been made of the interval between positional maxima of C1 and C2, the apex position for the tongue body in /k/ (bottom track) and the tongue tip in /r/ (top track). The duration of the lag between C1 and C2 maxima in this particular token is 144 ms. The lower lip peak for the following /v/ (middle track) is shortly after the C1–C2 lag.

We also measured the acoustic duration of C2 (C2Dur), along with a normalized version (C2/V) obtained by dividing by the C2 duration of the following vowel. Larger values for the C2 measures were indicative of more asynchronous cluster production, under the assumption that the larger portion visible for C2 annotation

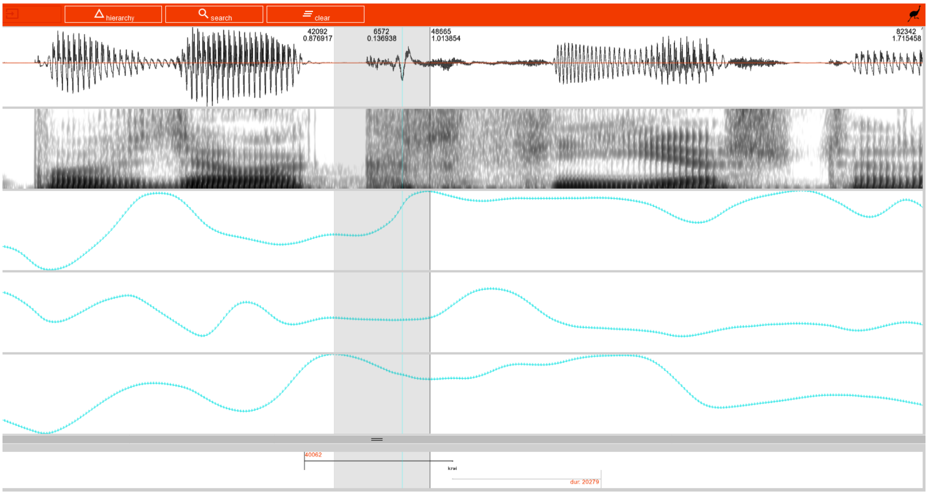

Figure 1: Illustration of target-to-target (t2t) lag measure between C1 and C2 in *krwi* 'blood'. Selected is the interval from tongue body maximum (bottom track) for /k/ to tongue tip maximum (top track) for /r/. The middle track is the lower lip.

was a sign that the C1 gesture had receded to the extent that it no longer obscured the visibility of C2 in the acoustic display.

The lag and C2 duration measures were plugged in as dependent variables in a series of linear mixed effects models, run in SPSS (IBM Corporation 2017) with cluster type (CC vs. CCC; phonotactic vs. morphonotactic), NAD values establishing the preferability of the clusters (Dziubalska-Kołaczyk et al. 2014), and within-pair differences in item frequency in the Subtlex-PL corpus (Mandera et al. 2014) as predictor variables, and speaker and item included as random factors.

4. Results

4.1. Two vs. three member onsets

An overview of the comparison of two and three member onsets is given in Table 1.

In the statistical analyses, the difference between two and three member onsets turned out to be significant for C2Dur ($p < .001$) and C2/V ($p = .026$), but not the t2t measures ($p > .05$). In the C2Dur measure, the C1C2 NAD value was a significant predictor ($\beta = -5.55$, St.E = 1.88, $t = -2.95$, $p = .005$). These effects are visible in Fig. 2. The preferred NAD values of /kr/ relative to /bz̨/ and /gz̨/ induced greater synchronicity (shorter C2), diminishing the effect of cluster size.

The effect of onset size for the C2Dur and C2/V measures held for four out of five speakers. This pattern is visible in the boxplots in Fig. 3, which shows individual results for C2Dur.

Type	Mean t2t/V	SD	Mean t2t (ms)	SD
CC	.9434	.51489	86.77	46.6
CCC	1.0002	.55695	89.93	41.7
Type	**Mean C2/V**	**SD**	**Mean C2Dur (ms)**	**SD**
CC	1.0404	.19523	98.65	26.36
CCC	1.3871	.55561	125.42	25.63

Table 1: Overview of results for 2 vs. 3 member onset comparison

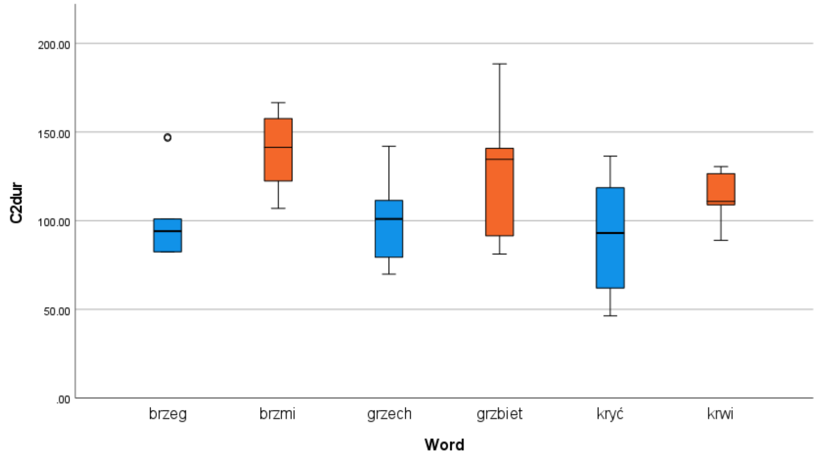

Figure 2: Boxplots for C2Dur measure as a function of item. Cluster type is shown by the colour of the boxplot: blue = CC; orange = CCC

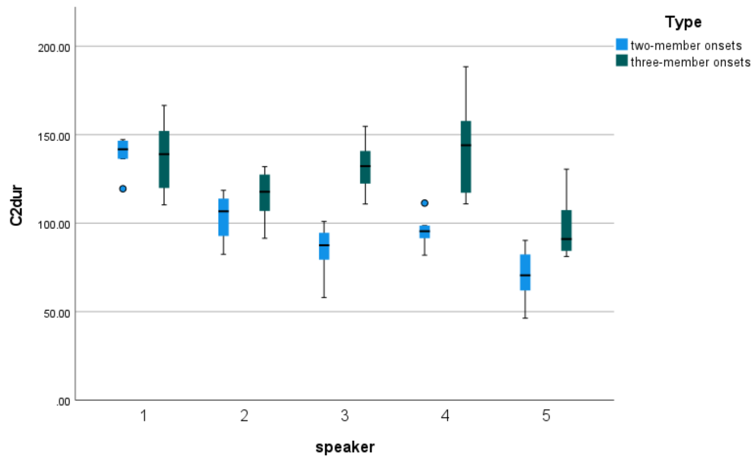

Figure 3: Boxplots of individual results for C2Dur measure, sorted for onset type (2 vs. 3 member)

Although the t2t measures revealed no effect of onset size, we observed that the /gʐ/ onset showed smaller lags than /bʐ/ and /kr/ across both CC and CCC clusters. Results for t2t/V as function of item are summarized in the boxplots in Fig. 4.

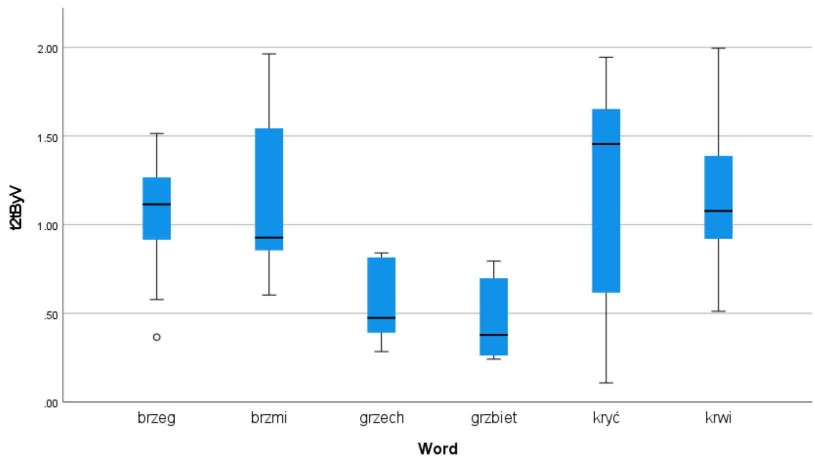

Figure 4: Boxplots of results for t2t/V measure as a function of experimental item

4.2. Phonotactic vs. morphonotactic clusters

An overview of the comparison of phonotactic and morphonotactic clusters is given in Table 2, which provides means and standard deviations of the t2t/V and C2/V measures as a function of cluster type.

Type	**Mean t2t/V**	**SD**	**Mean t2t (ms)**	**SD**
morphonotactic	.9941	.23865	97.53	27.96
phonotactic	1.3209	.49010	97.22	32.89
Type	**Mean C2/V**	**SD**	**Mean C2Dur (ms)**	**SD**
morphonotactic	1.1010	.33204	106.17	27.42
phonotactic	1.3148	.42381	96.06	26.93

Table 2: Overview of results for phonotactic vs. morphonotactic cluster comparison

In the statistical analyses, the difference between morphonotactic and phonotactic clusters turned out to be significant for the t2t/V measure ($p = .028$), but not the other measures ($p > .05$). No other predictors were significant. A visualization of the results for the t2t/V measure is given in the boxplots in Fig. 5.

Unlike the two vs. three member onset comparison, in which one speaker did not show the same overall effect, in the phonotactic vs. morphonotactic comparison the effect was more consistent across the five speakers, as seen in Fig. 6.

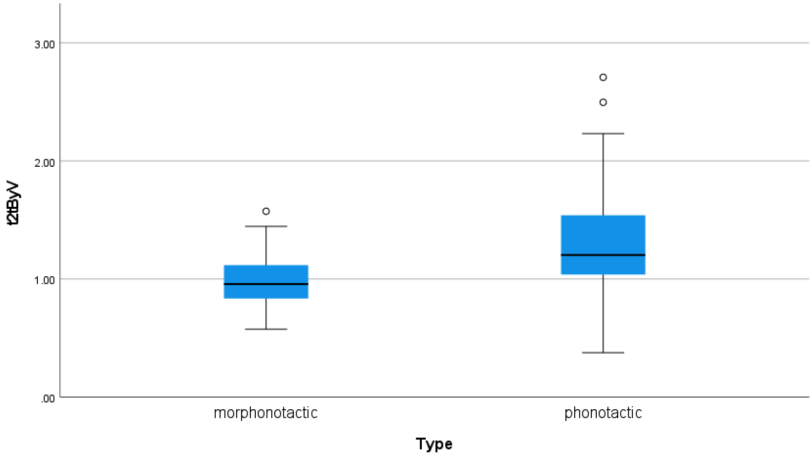

Figure 5: Boxplots of results for t2t/V measure as a function of cluster type (phonotactic/morphonotactic)

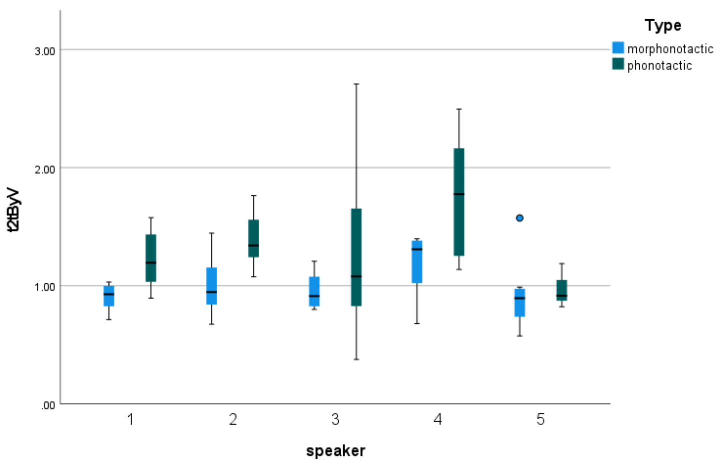

Figure 6: Boxplots of individual results for t2t/V measure sorted for cluster type (phonotactic/morphonotactic)

Looking at individual items, we see that the effect by which morphonotictic clusters showed shorter lags held for 3 out of 4 of the pairs. This is shown in Fig. 7, with items containing phonotactic clusters represented by the blue boxplots, and morphonotatic clusters shown by the orange boxplots.

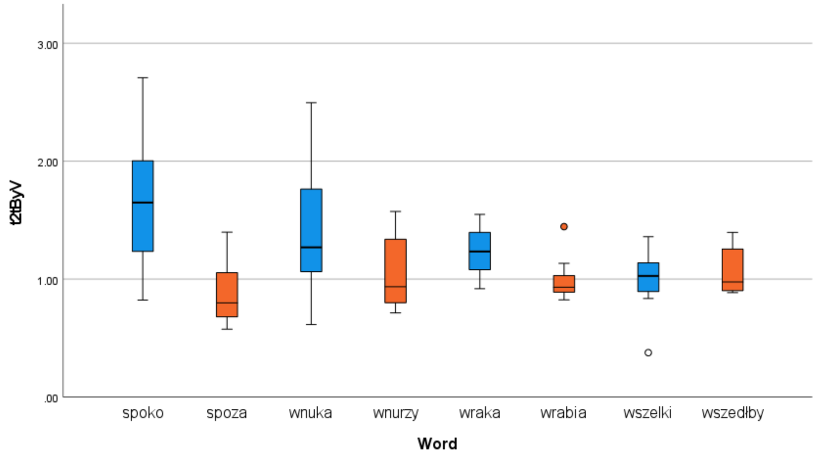

Figure 7: Boxplots for t2t/V measure as a function of item. Cluster type is shown by the colour of the boxplot: blue = phonotactic; orange = morphonotactic

5. Discussion

In this section we attempt to interpret the results of our experiment.

With regard to the 2-vs-3-member onset comparison we found less synchronicity between C1 and C2 in CCC clusters than between C1 and C2 in CCV sequences. This result was found in the acoustic duration of C2 (Fig. 2 and 3). From the perspective of listener-oriented theories of speech production, such as Lindblom's (1990) H&H Theory, this finding may be explained by the need to increase perceptibility of the second consonant in a pre-consonantal context. H&H Theory operates under a principle of sufficient discriminability. Since preconsonantal consonants are less perceptually robust than pre-vocalic ones, due to the lack of CV transition cues to their identity (e.g. Wright 2004), sufficient discriminability may demand that speakers lengthen C2 in three member onsets as a way of making C2 easier for listeners to hear. This motivation may be bolstered by the "marked" nature of three-member onsets, as expressed by theories of cluster well-formedness (e.g. Dziubalska-Kołaczyk 2014). That is, a more "marked" cluster may induce a more careful pronunciation in which C2 is lengthened. In this connection, the /kr/ cluster with the highest C1C2 NAD value (least marked) in our study contributed to greater synchronicity by lowering C2 duration. In future work, we plan to examine a larger inventory of clusters to more thoroughly investigate the effects of cluster well-formedness on cluster synchronicity.

With regard to the morphonotactic vs. phonotactic comparison, we find greater synchronicity in clusters spanning a morpheme boundary (Fig. 5, 6, and 7). At first glance, this finding might be unexpected. Instead of inducing greater separation between consonants, the boundary present in the morphonotactic clusters apparently had the opposite effect. However, an explanation may be found if we again consider a listener-oriented perspective. Presumably, speakers have some awareness that the cluster spans a morpheme boundary. They may therefore make a subconscious assumption that the listener too is aware of the boundary and will be able to reconstruct it (see Ohala 1981). Thus, they may spare themselves the effort of producing a more asynchronous consonant sequence.

This interpretation would be compatible with perceptual findings on word boundaries in Polish. Schwartz (2017) found that glottalization on word-initial vowels, a frequent process associated with morpheme boundaries, did not facilitate perception of the boundary – boundaries with or without glottalization were identified equally well. This result may have been because listeners were already aware of the boundary's presence. In other words, there is evidence that Polish listeners are adept at identifying boundaries, so speakers can eliminate them in production. A similar explanation may underlie our result in which boundary-spanning clusters were produced with greater synchronicity than the same clusters within boundaries.

At the same time, in future work, it will be necessary to consider a larger number of items, and compare the strength of boundaries. In a study using ultrasound imaging, Ćavar et al. (2023) found that the relative strength of the prosodic boundary was predictive of degree of assimilation in cross-boundary sequences of coronal consonants – stronger boundaries reduced the degree of assimilation. Thus, at first glance, a comparison of the present results with those of Ćavar et al. (2023) seems to present a discrepancy, since in the present study boundaries induced greater phonetic synchronicity. One important difference between the two studies, however, is that the consonant clusters examined here were heterorganic (coronal-labial or labial-coronal), while Ćavar et al. (2023) looked at coronal-coronal sequences. In Polish, homorganic consonant sequences (including geminates) often behave differently from heterorganic clusters with regard to C1 release or cluster reduction (Zembrzuski 2014). For example, coda stops in Polish are always produced with an audible release, except when they appear in homorganic clusters (Dukiewicz and Sawicka 1995). Thus, in a word such as *wódka* /vɔdka/ 'vodka', the coronal stop is always released (devoiced to [t] in this case), while release of the /d/ may be suppressed in a word such as *ładny* /wadnɨ/ 'pretty'. Thus, it is not at all unexpected that the clusters analyzed by Ćavar et al. (2023) behaved differently from the ones examined here. The differences in phonetic behaviour between homorganic and heterorganic clusters in Polish are well documented.

This paper has presented new articulatory data on two understudied aspects of consonant cluster production in Polish: the role of cluster size and the role of morpheme boundaries in determining the degree of phonetic synchronicity in the production of the consonant sequences. In interpreting our results, we are of course aware of the main limitations of the study, i.e. the relatively small number of speakers, and the small number of experimental items. Nevertheless, since we are unaware of studies on Polish addressing the questions examined here, we feel that it is worth reporting on these results in the hope of inspiring additional research in the future.

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